1976

Slam loading for use in hull girder : response analysis.

Walker, William Francis

SLAM LOADING FOR USE IN HULL
GIRDER RESPONSE ANALYSIS

William Francis Walker

SLAM LOADING FOR USE IN HULL GIRDER RESPONSE ANALYSIS

by

WILLIAM FRANCIS WALKER

B.S., Purdue University
(1971)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE IN

OCEAN ENGINEERING

at the

Massachusetts Institute of Technology

January, 1976

SLAM LOADING FOR USE IN HULL GIRDER

RESPONSE ANALYSIS

by

WILLIAM FRANCIS WALKER

Submitted to the Department of Ocean Engineering on January 21, 1976, in partial fulfillment of the requirements for the degree of Master of Science in Ocean Engineering at the Massachusetts Institute of Technology.

ABSTRACT

This work reviews the existing literature on slam force prediction methods and discusses some of the theory of ship bottom slamming. One of these prediction methods is chosen as the best and further improvements are made on it by using a new model of slamming.

The work is designed to determine a slam forcing function suitable for studying ship hull girder dynamic response. Slam forces are determined by integrating the pressure time history over the portion of the hull subject to slamming. A computer program is included which determines the slam forces and impulses from the ship's lines, principal dimensions, and seakeeping data. The method is applied to two ships, the MARINER and the FOTINI-L, and the results presented.

Thesis Supervisor: Professor J. H. Evans
Title: Professor of Naval Architecture

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Professor J. H. Evans, Professor J. K. Vandiver, and Mr. R. G. Kline for their guidance and encouragement in this work. I would also like to thank the American Bureau of Shipping for financing the computer costs and the United States Navy for this postgraduate education opportunity.

Most of all I would like to thank my wife without whose love and encouragement this work would never have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES, CONTINUED

LIST OF TABLES

LIST OF SYMBOLS

A	Sectional area
A'	Half-section area at 1/10 design draft
B	Maximum molded breadth of load waterline
B'	Half-breadth at 1/10 design draft
C_{air}	Speed of sound in air
C_B	Block Coefficient
D	Molded depth
$f(p)$	Slamming probability distribution function
$F(p)$	Cumulative probability distribution function
F	Froude number
g	Acceleration due to gravity
$\overline{H(1/3)}$	Significant wave height
I_ℓ	Local slam impulse / in^2
k	Section form coefficient
L	Ship length
l_s	Length of slam region
l_o	Half-width of infinitely long flat plate
LBP	Length between perpendiculars
m	Added mass per unit length
m_o	r.m.s. value of response
m_o'	r.m.s. value of response with broadness correction
m_k	k^{th} moment of the spectrum
N_s	Number of slams per second
$N(t)$	Number of slam impacts in t hours

n	Number of impacts
P	Slam force
P_1	Inertial slam force
P_2	Buoyant slam force
p	Pressure
p_o	Threshold pressure = $k\ \dot{r}_*^2$
p_n	Extreme value of pressure in n finite number of impacts
$\hat{p}_n(\alpha)$	Extreme pressure for design
$\overline{p_n}$	Most probable extreme pressure in n observations
$\dot{r}$	Impact velocity
$\dot{r}_*$	Threshold velocity
R'_r	Twice variance of relative motion
$R'_{\dot{r}}$	Twice variance of relative velocity
S	Non-dimensional sea state
t	Time
T	Draft
t_i	Time of local slam initiation
t_1	Duration of local slam pressure
t_2	Duration of triangular slam force approximation at one half-station
T'	1/10 design draft
TSTORM	Time of storm
t_t	Time slam takes to travel from aft extent of slam to slam center
v_t	Traveling velocity

VEL	Relative velocity of slam center
w_r	Relative velocity
x	Longitudinal ship coordinate axis
X	Distance from slam center
α	(alpha) probability the extreme pressure for design will be exceeded
β	(beta) angle between the normal to the section line and the vertical
ε	(epsilon) broadness factor correction
λ	(lambda) $1 / (k\ R_r^!)$
ρ	(rho) mass density

I. INTRODUCTION

The primary objective of this thesis is to review the existing literature on slamming and to develop a method of predicting slam forces to determine hull girder response. This project is a portion of an overall study presently underway at M.I.T. sponsored by the American Bureau of Shipping (A.B.S.) on hull stiffness criteria.

Presently, explicit criteria for ship stiffness do not exist. The ship classification societies have controlled stiffness or deflections by limiting allowable Length to Depth (L/D) ratios [1]*. With the introduction of new materials such as high strength steels and aluminum in ship construction, the question of stiffness and what should be allowed becomes more important.

Considering the present L/D ratios as hull girder stiffness criteria, what other factors that affect stiffness could be used in design? Bending stiffness of a ship's hull can be varied within reasonable limits by the following means:

1. By changing the basic hull depth,
2. By designing to higher stress levels with higher strength steels, and
3. By using materials with different elastic moduli.

Since other factors can more properly be used to control stiffness other than L/D, it is not satisfactory to use this as a

*Numbers in square brackets designate References at the end of the paper.

criterion for design. Probably a new criterion based specifically on a measure of stiffness should be used.

Before any quantitative information could be developed for limiting hull stiffness, factors which would be changed by stiffness variations were assessed [2]. Assuming strength criteria are maintained, stiffness variations will result in changing factors which determine hull girder dynamic response. In the Reference [2] report it was concluded that the factors of ship stiffness which should be of concern were:

1. Slamming response for its contribution of stress components, especially amidships,
2. springing for its cumulative stress effects, and
3. steady-state propeller-excited vibratory motions and their deleterious effects upon personnel and main machinery components.

Although propeller-excited vibratory motions will change with hull stiffness variations, it is felt that these problems can be dealt with by more efficient and less costly methods than changing the hull girder stiffness. Therefore the primary factors of concern are slamming and springing response with variations in hull stiffness.

In the overall study the Kline-Clough lumped-mass vibration program, S.H.V.R.S., has been used to analyze the ship response to slamming and springing [3]. Several ships have been looked at in great detail. Some of the results have been reported in references [3] and [4]. To date, in this work on

slamming, a constant slam impulse of 100 Ton-seconds has been used in the response analysis modeled as a half sine pulse applied at a single location. Results, such as stress levels, other than trends in response due to changes in stiffness, could not be determined until a better model of the slam force and a satisfactory means of evaluating force magnitudes from ship to ship could be found.

The purpose of this work is to develop a model of the bottom impact slam force compatible with the S.H.V.R.S. program which will require a minimum of manhours and computer time yet give adequate results. The bottom impact slam force developed here is a function of hull form, ship speed, and sea state. A computer program is developed which predicts the most probable slam force as well as an extreme force to be used for design. Other slam information is also available such as frequency of slamming and slam pressures useful in designing hull plating.

II. BOTTOM IMPACT SLAMMING

For this study the bottom impact slam is defined as the "heavy blow" resulting from the forebody hitting the water surface at a high relative velocity. This is in contrast to the phenomenon of bow flare slamming which is a consequence of emersion of the bow flare and the resultant hydrodynamic and hydrostatic forces. Much of the work to date has been in the form of predicting the local pressures developed to study plating damage. That can be considered the micro-problem. In this work we are concerned with the macro-problem which involves hull vibrations and possibly large midship stresses.

Oakley [5] has analyzed the micro-problem in great detail. There are many factors that have been observed to measurably affect the pressure history. These factors include the following: shape, velocity, and phasing of the surface waves; geometry of the hull and hull reaction characteristics; air and water compressibility; two and three-dimensional air and water flow; bubbles, spray, and even such things as marine growth. Due to the complexity of the problem and the randomness of the sea, model testing and statistics play an important role in the solution to the slamming problem.

Tick [6] developed the equation for the frequency of slamming which is dependent on the following:

1. forefoot emergence statistics,
2. relative velocity statistics, and
3. the angle between the keel line and the wave surface at the instant of impact.

In most work to date the equation is simplified to remove the angle dependence and only the requirements of (1) forefoot emergence and (2) a relative velocity greater than a threshold velocity are considered necessary for slamming. Neglecting this angular dependence results in overpredicting the frequency of slam impact as well as the slam force. A method of dealing with the angular dependence is presented in Section IV of this work. The two requirements for slamming are met by the ship in Figure 1. Using Tick's equation without angular dependence allows prediction of the frequency of slamming and is the basis of slam calculations in seakeeping programs [7]. The one necessary input to seakeeping programs is the threshold velocity. How this is determined and the value to be used is discussed in Section IV.

From Tick's work it is possible to conclude whether or not a ship is subject to slamming under a particular set of operating conditions, in particular the ship speed, sea state and draft at the station under consideration. Given that slamming does occur, the next step is to determine the slam force. Two basic methods have been used in the past: (1) integration of the slam pressure time histories over the slam area; and (2) determine an analytical solution based on the rate of change of momentum. In Section III both methods are discussed and one selected for this study.

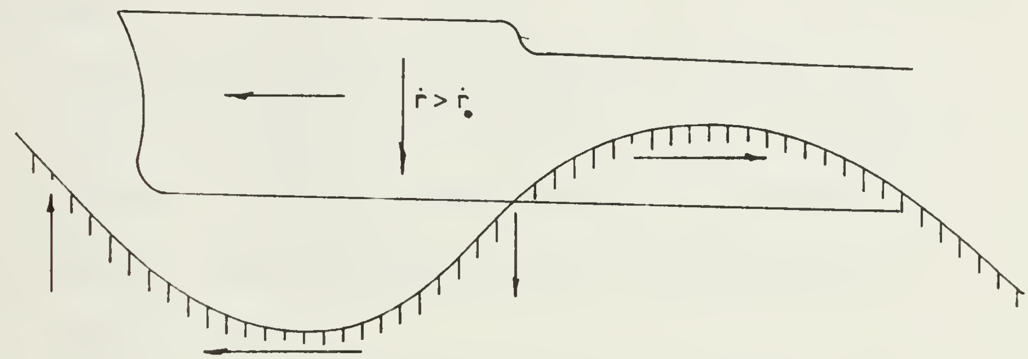

FIGURE 1 - SHIP SLAM CRITERIA

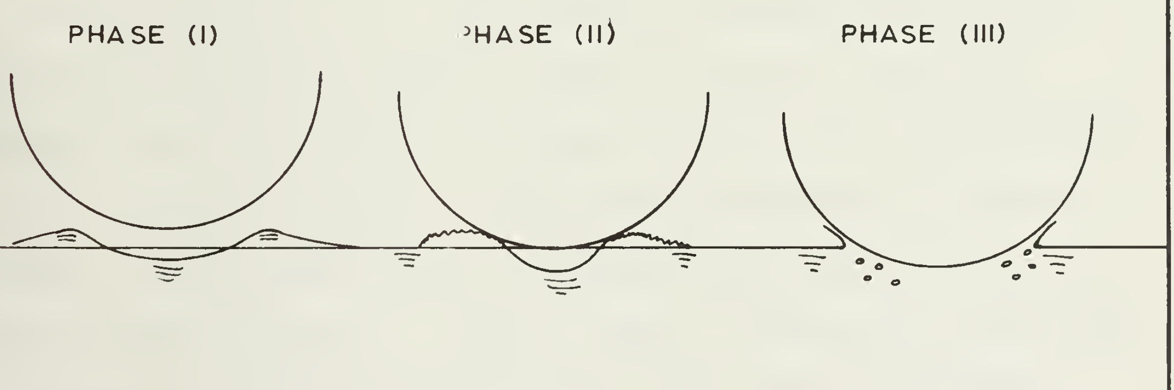

FIGURE 2 - PHASES OF SLAMMING

Before comparing the two methods, some discussion is in order with respect to the mechanism of slamming. Oakley [5] considered the time history of slamming to be made up of three phases:

1. Phase (I) is the time in which the body is approaching the free surface up until it makes contact. In this phase the air flow and the surface wave deflection are of predominant importance.
2. Phase (II) is the period when the body goes through the free surface and involves the problem of "contact" and more or less complete wetting of the hull.
3. Phase (III) is the fully wetted problem in which the rate of change of added mass and the local surface deflection are dominant.

A very flat body or "U" form hull may accelerate the free surface significantly during phase (I) while a more "V" shaped section may develop greatest forces only during phase (III). Figure 2 shows the relationship between the three phases. Much of the work to date has dealt with only one or two of these phases at a time. This is especially true with the many two and three-dimensional drop tests performed. Chuang [8] and others have demonstrated the important role of the air in accelerating the free surface in phase (I) and as a cushioning mechanism in phase (II). The wedge-entry

problem has been studied by many authors, most recently by Chuang [9], and agreement for large deadrise angles (phase (III) only) is good. The theory breaks down for low deadrise angles where phase (I) and phase (II) become important.

Therefore any solution to the slam forcing function should take into account the forces developed during all three of the phases unless one phase can be shown to be much greater than the others. At this time it appears that neglecting phase (I) and phase (II) is only valid for "V" form sections.

III. SLAM FORCE PREDICTION METHODS

During the last twenty years a great deal has been written on slamming, attesting to the difficulty of a satisfactory solution to the problem. Much of the work has been done along with ship vibration analysis techniques. This study does not go into the question of structural response. It is felt that adequate methods exist for analyzing the structural response of a ship if the various forcing functions can be adequately represented. The S.H.V.R.S. program described in Reference [3] which has been used in this overall study has been shown to give satisfactory results. Therefore the model of slam force was chosen with the S.H.V.R.S. program in mind.

The slam force prediction methods are of two types:

1. The slam force is considered as resulting from the rate of change of momentum of the added mass of the ship with a buoyancy correction term. This method will be called the momentum method.
2. The second method consists of determining the slam pressure and integrating spatially as well as temporally over the slam area. This method will be designated the slam pressure method.

Both of these methods were considered and the second was considered more valid and more easily applicable to the overall stiffness study.

RATE OF CHANGE OF MOMENTUM METHOD

As early as 1956 Szebehely [10] proposed that the slam force was a result of the rate of change of momentum of the added mass in the region of the slam. Further studies by Leibowitz [11] used this model of slamming to analyze the slam forces on a Dutch destroyer. Good results were obtained between the theory and full scale results for bow flare slams. More recently Mansour and d'Oliviera [12], [13] have utilized the same slam force function to predict slam bending moments in regular waves.

The slam force (P) is considered as the sum of an inertial term (P_1) and a buoyancy term (P_2) and is given by

$$
\begin{aligned}
P(x,t) &= P_1(x,t) + P_2(x,t) \\
&= \frac{D}{Dt}(mw_r) + \rho gA \qquad (1) \\
&= \frac{\partial}{\partial t}(mw_r) + \frac{\partial}{\partial x}(mw_r)\,\frac{dx}{dt} + \rho gA
\end{aligned}
$$

where $m = m(x,t)$ is the added mass per unit length, w_r is the relative vertical velocity between the wave and the ship, and A is the sectional area. The total derivative is used ($\frac{D}{Dt}$) since the rate of change of momentum occurs not only temporally but also spatially.

It should be noted that this is the phase (III) problem described by Oakley. No account is made for the force which comes during phase (I) and phase (II) of the slam process. It

is expected that this method should show good results for "V" form hulls and bow flare slamming only. The major drawback to this approach, even if it were valid for the bottom impact slam case, is it requires a large amount of seakeeping information to determine $m(x,t)$. In reality the added mass must be determined as a function of draft at each station and frequency of encounter for each wave considered. To obtain this information requires a large expenditure in manhours and computer time. The end result is also valid only for regular waves.

SLAM PRESSURE PREDICTION METHOD

A great deal of the initial work in this area has been done to solve the micro-problem--that is, to determine the slam pressure locally for plate design information. Much of the work in this area has been done by M.D. Ochi, K.M. Ochi, and S.L. Chuang at the Naval Ship Research and Development Center. A summary of the slamming studies to date appears in Reference [14]. In this work by M.K. Ochi and Motter they develop the basic theory behind the approach to slamming prediction in this method.

In this approach the pressure is considered as a function of velocity of impact and section shape only. The slam pressure is given by

$$p = k\dot{r}^2 \tag{2}$$

where k is a parameter to be determined from section form and $\dot{r}$ is the velocity of impact.

From the many two and three-dimensional drop tests as well as full scale measurements and model tests it has been found that equation (2) holds quite well for slam impact problems. Therefore once the form coefficient (k) can be determined for each section, the slam impact pressure can be determined if the velocity of impact is known. Since relative velocities are easily determined from seakeeping programs, knowing the value of k for each section allows for the determination of the slam pressure which can be integrated over the hull form to determine the slam force.

This second approach has the advantage that the form coefficient k is obtained from model data which includes the contribution from phase (I), (II), and (III) forces. In addition, recent work by Loukakis and Chryssostomidis [15] make available the seakeeping information necessary for slam studies for ships that can be approximated by Series 60 hull forms.

The slam pressure approach was chosen since it requires a minimum of seakeeping information, is applicable to all hull forms, and the results are applicable in irregular seas. Unlike most engineering problems it also turns out that this approach is easiest to apply.

IV. PRINCIPLES AND PROCEDURE OF THE SLAM PRESSURE METHOD

Ochi and Motter's work described in Reference [14] presents the theory and assumptions of the slam pressure method. In trying to apply the method it appeared that some of their assumptions resulted in overpredicting the slam force and impulse. In this section the theory and assumptions made by Ochi and Motter are discussed and modified where the assumptions were not felt fully justified. The following topics will be discussed in developing the method:

1. Frequency of slam impact,
2. Slam pressure and hull form coefficient,
3. Most probable extreme pressure,
4. Extreme pressure for design,
5. Sea state data and approximation for storm duration,
6. Slam impact area of the hull, and
7. Slam impact force and impulse.

FREQUENCY OF SLAM IMPACT

Tick [6] derived the equation for the frequency of slam impact at the bow which is dependent on the relative velocity, relative motion, and angle between the keel and the wave surface. By integrating over all angles to neglect the angular dependence,

$$N_s = \frac{1}{2\pi}\sqrt{\frac{R'_{\dot{r}}}{R'_r}} \quad Pr\ \{\text{slam impact}\}$$

$$N_s = \frac{1}{2\pi}\sqrt{\frac{R'_{\dot{r}}}{R'_r}} \quad \exp\ -\left(\frac{T^2}{R'_r} + \frac{\dot{r}_*^2}{R'_{\dot{r}}}\right) \tag{3}$$

where N_s = Number of slams per second

T = Ship draft at station under consideration

$\dot{r}_*$ = Threshold velocity

R'_r = Twice variance of relative motion

$R'_{\dot{r}}$ = Twice variance of relative velocity

The number of impacts in a storm of duration t hours, N(t), is then given by

$$N(t) = \frac{3600\ t}{2\pi} \sqrt{\frac{R'_{\dot{r}}}{R'_r}} \exp -\left[\frac{T^2}{R'_r} + \frac{\dot{r}_*^2}{R'_{\dot{r}}}\right] \qquad (4)$$

Different values of the threshold velocity below which slamming does not occur have been used, but following Ochi's work [14],

$$\dot{r}_* = 12\sqrt{\frac{L}{520}} = 0.53\ \sqrt{L} \qquad (5)$$

will be used where $\dot{r}_*$ = 12 feet/sec for a 520 FT ship and the Froude scaling law is applied. Because some of the slams predicted by equation (4) will occur above the angle which will cause slamming, equation (4) will overpredict the number of slams. This number is used to determine the extent of slam area and slam pressure. Overestimating N(t) will yield a larger slam area as well as a slightly higher pressure. The assumption is made that slamming will still occur forward of the area that is overestimated and that the pressure can be corrected by a relative angle correction. This will be discussed later.

SLAMMING PRESSURE AND HULL FORM COEFFICIENT (k)

To estimate the slam pressure it is necessary to find a functional relationship for pressure vs. velocity. As mentioned earlier, it has been shown that equation (2)

$$p = k \dot{r}^2$$

holds very well and can be used if the form coefficient, k, can be determined.

Ochi and Motter [16] used mapping and regression analysis techniques to find the k values from experimental data. This method was used to develop a computer program reported in Reference [16] to determine the coefficients. This program was used as a subroutine in this work but it did not give satisfactory results for broad beam sections. The regression analysis had been performed over relatively narrow ship sections and the confidence range for the coefficients was 0.073 to 0.190 with 10% risk of error. In applying their program two problems developed:

1. The k values for broad beam flat sections were well outside the 0.190 confidence figure; and
2. The mapping blew up in many of the broad beam cases.

Since many ships of commercial interest could not be covered by the program, another method had to be found for these wide forms.

M.D. Ochi [17] in work which was an attempt to correlate the k values from two and three-dimensional drop tests as well as model tests proposed that the following holds:

$$k = 0.02 \frac{B'^2}{A'} \tag{6}$$

where B' = half-breadth at 1/10 design draft

A' = half-section area at the 1/10 design draft

This work, which was done prior to the regression analysis technique in Reference [16], was compared to the results obtained by the computer program. Better agreement inside the confidence range was obtained if a slightly higher constant was used. Therefore it is assumed that

$$k = 0.027 \frac{B'^2}{A'} \tag{6a}$$

In the program developed in this thesis, equation (6a) is used when section values above 0.190 are obtained from the regression subroutine. This is done since equation (6a) yields larger k values and high pressures which is more conservative.

Now that the form coefficients can be calculated, it is possible to determine the maximum pressure at each station along the ship if the velocity of impact can be found.

MOST PROBABLE EXTREME PRESSURE

The impact relative velocity is approximated by the amplitude of relative velocity which is a random variable following the Rayleigh probability distribution [14]. Using equation (2) and the Rayleigh distribution function, the slamming probability distribution function is given by

$$f(p) = \lambda \exp\left[-\lambda (p - p_o)\right] \tag{7}$$

$$p_o \leq p < \infty$$

where p = slamming pressure

p_o = threshold pressure = $k\dot{r}_*^2$

$\lambda = 1/(k\, R_{\dot{r}}')$

By applying order statistics to the probability distribution (7), the distribution of extreme value of pressure in n finite number of impacts, p_n, is given by

$$f(p_n) = \left[n\, f(p)\, \{F(p)\}^{n-1}\right]_{p=p_n}$$

$$= n\lambda \exp\left[-\lambda (p_n - p_o)\right] \{1-\exp[-\lambda (p_n - p_o)]\}^{n-1} \tag{8}$$

$$p_o \leq p_n < \infty$$

where

$$F(p) = \int_{p_o}^{p} f(p)\, dp$$

From equation (8) it is possible to derive the most probable extreme pressure in n-observations, $\bar{p}_n$. Figure 3 shows the probability distribution function given by equation (8). The most probable extreme pressure, $\bar{p}_n$, can be obtained by setting the first derivative with respect to p_n equal to zero.

$$\frac{d\, f(p_n)}{d\, p_n} = 0 \tag{9}$$

Using equations (8) and (9), $\bar{p}_n$ is obtained

$$\bar{p}_n = k(\dot{r}_*^2 + R'_{\dot{r}} \ln(n)) \tag{10}$$

This most probable pressure can be used to calculate slam forces and is one of two pressure options in the computer program.

EXTREME PRESSURE FOR DESIGN

Although it may be reasonable to compare $\bar{p}_n$ with the largest value observed in experiments, the probability that a pressure is higher than $\bar{p}_n$ is 0.632. Since the probability distribution function, equation (8) as plotted in Figure 3, is never zero at high pressures, the extreme pressure for design can be determined only if a small probability of being exceeded (α) is allowable. The extreme pressure for design, $\hat{p}_n(\alpha)$, can be found from

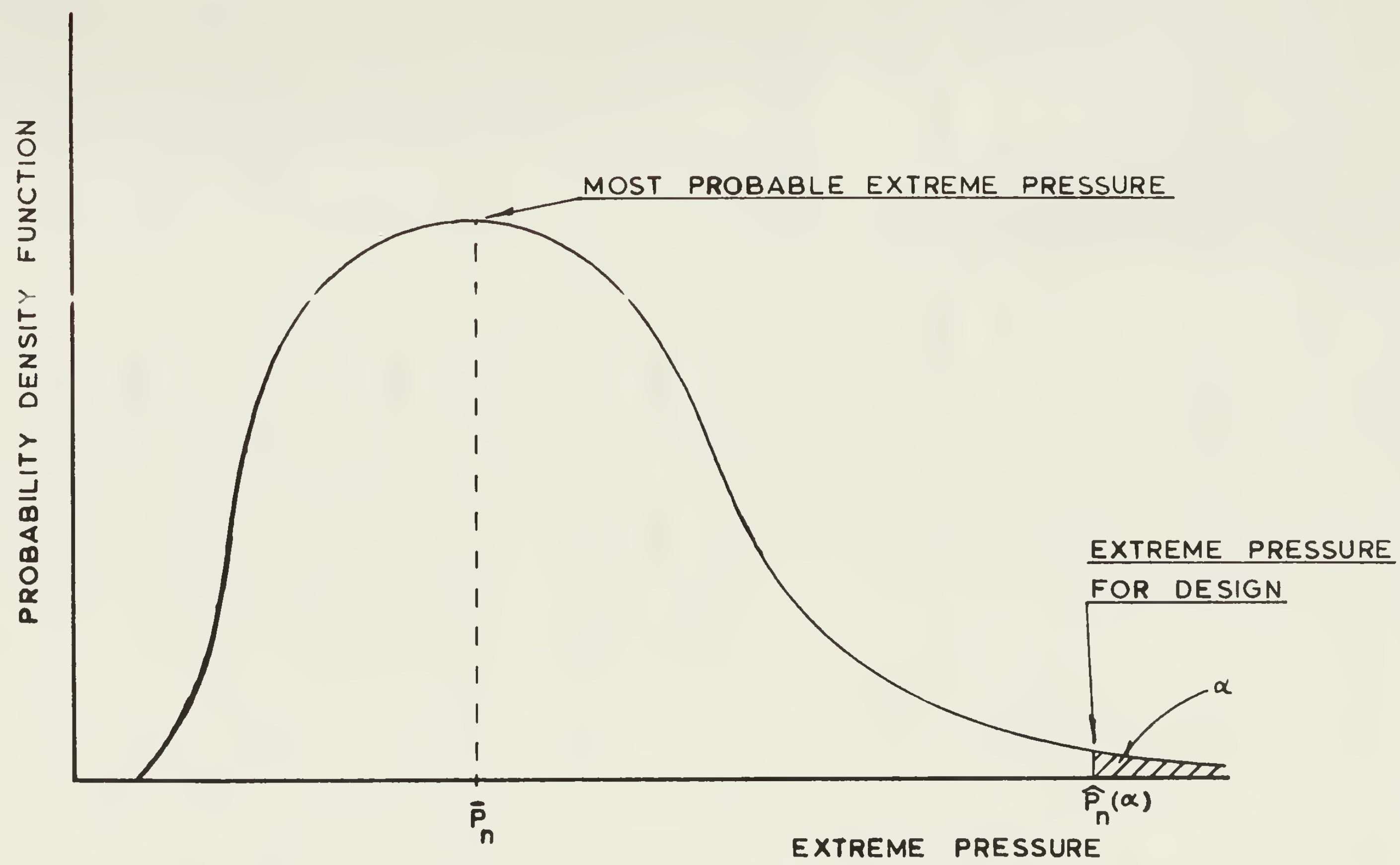

FIGURE 3 - EXTREME PRESSURE PROBABILITY DENSITY FUNCTION

$$\int_{\hat{p}_n}^{\infty} f(p_n)\, d\, p_n = \alpha \tag{11}$$

Using equations (8) and (11)

$$\hat{p}_n(\alpha) = k\, [\dot{r}_*^2 - R_{\dot{r}}'\, \ln\{1-(1-\alpha)^{1/n}\}] \tag{12}$$

The extreme pressure for design is controlled by the pre-assigned small probability, α , which can be specified by the designer. In the calculations in the computer program Ochi's [14] value of $\alpha = 0.01$ is used, but can be changed if desired.

SEA STATE INFORMATION

In the calculations necessary to determine slam pressures the sea state must be specified to determine

1. the relative motions and velocities and
2. the duration of the storm

in order to calculate the number of slams from equation (4).

In order to make the application of the program as simple as possible, the only parameter which needs to be specified is the significant wave height, $\overline{H(1/3)}$. This is made possible by the work done by Loukakis and Chryssostomidis [15] from which the r.m.s. relative motions and r.m.s. relative velocities may be determined for the forward stations using only the parameters of:

1. C_B = Block coefficient
2. L/B = Length to Beam ratio

3. B/T = Beam to Draft ratio

4. $\overline{H(1/3)}/L = S$ = Non-dimensional sea state

5. F = Froude number = SHIP SPEED/$\sqrt{gL}$

These parameters are sufficient to give good initial design values for relative motion and velocity. There is also a dependence on longitudinal center of flotation and radius of gyration but it is not particularly sensitive to these parameters [15]. These tables were developed from Series-60 hull forms and, therefore, can only be used for ships which can be approximated by these forms. This allows calculation of slam forces for these ships without running seakeeping programs. The option is also available to specify the relative motions and velocities if desired.

The storm duration also needs to be known. Following Ochi and Motter [14], wave records have been analyzed in the North Atlantic. A plot of the envelope of storm duration vs. significant wave height is shown in Figure 4. This envelope is used to determine the maximum duration to be expected for a ship operating at the significant wave height. This envelope is the default option in the program and is considered the extreme storm for design. If desired, a storm duration may be specified in the input data to the program

FIGURE 4 - STORM DURATION vs. SIGNIFICANT WAVE HEIGHT

SLAM IMPACT REGION

Using the time of storm from the previous section as well as the tabulated r.m.s. motions and velocities, equation (4) can be evaluated at each station considered to determine the number of slams during an extreme storm. The number of slams is greatest at the bow and decreases rapidly as the midships crossection is approached. The sections where $N(t) \geq 1$ is assumed to be the longitudinal extent of slamming.

From model tests and drop tests [17] it has been found that the slam pressure is essentially dissipated at a depth of 1/10 of the design draft, T'. Therefore the pressure needs to be integrated only over the forward portion of the hull where $N(t) \geq 1$ and below 1/10 design draft.

SLAM FORCE AND IMPULSE

The information is now available to determine the most probable and extreme pressure for design $\bar{p}_n$ and $\hat{p}_n(\alpha)$ at the keel for each station as well as the slam impact area for a particular ship, speed, and sea state. To integrate temporally and spatially, more information is needed about the spatial variation of pressure in the girth direction as well as the time history of the slam.

The local pressure time history as used by Ochi [14] is shown in Figure 5. The duration of the slam pressure, t_1, is given by

$$t_1 = 0.1 \sqrt{L/520} = 4.4 \times 10^{-3} \sqrt{L} \qquad (13)$$

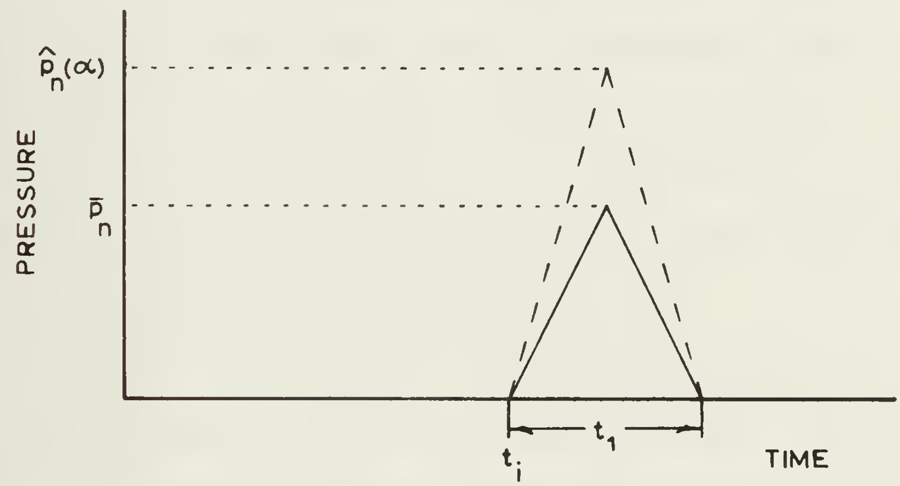

FIGURE 5 - SLAM PRESSURE TIME HISTORY

which is an average for a 520 FT vessel whether it is in the flat bottom region or the bilge. Froude's scaling law is used for ships of different lengths. The slam pulse is assumed triangular with equal rise and fall times. The duration of slam is one area where it is felt additional work needs to be done. In Appendix A an alternate equation for t_1 is considered and presented here as equation (14).

$$t_1 = 3.6 \times 10^{-3} B' \quad \text{(seconds)} \tag{14}$$

where B' = Half-beam at 1/10 design draft in feet

Until further work can be done to experimentally determine which time duration is best, either can be used. The computer program uses equation (13) but it is felt by this author that from the analysis of drop test results beam should be used as the scaling parameter instead of length.

The work done by Ochi assumes that there is no dependence on angle between the keel and wave surface, and that the worst slam case is when the slam pressure travels the full extent forward or aft at the slowest traveling velocity. It is felt that the wave slope has a large effect in reducing the slam forces predicted by Ochi's slam model. Therefore a new model of slam is proposed which accounts for the dependence on wave slope.

Numerous experiments have shown that the slamming becomes maximum in regular waves when the ship encounters waves of length L_w on the order of 1.0 to 1.1 times the ship length, L,

[12], [18]. It is assumed that a similar condition has been approximated in irregular seas leading to the worst slam condition. For the relative velocities to be maximum, the ship will be pitching down in the vicinity of zero pitch angle. For this to occur the slam will take place in the trough of the wave. Figure 6 depicts this model of slamming. The slam pressure will travel from the forward perpendicular aft and from the aft slam station forward meeting at what is called here the slam center. Assuming the wave encountered has height equal to the significant wave height allows calculation of the slope between the keel and the wave surface. This angular dependence will be used to modify the slam pressures from what would be expected for flat impact.

Chuang [9] performed a series of drop tests with varying deadrise angles. It is proposed here that the reduction in pressure with deadrise angle can be used for similar angles in the longitudinal direction. Figure 7 is taken from Reference [9] and shows a significant reduction in pressure with deadrise angle. The region between 0 and 3 degrees is where the compressibility of the air comes into effect. It is assumed this is not as pronounced in the longitudinal direction due to the escape of air in the transverse direction. The higher angles are almost linear when plotted on $\log_{10}$ paper and the slope remains almost constant for all impact velocities. From the linear region of Figure 7 a correction equation for pressure was found as

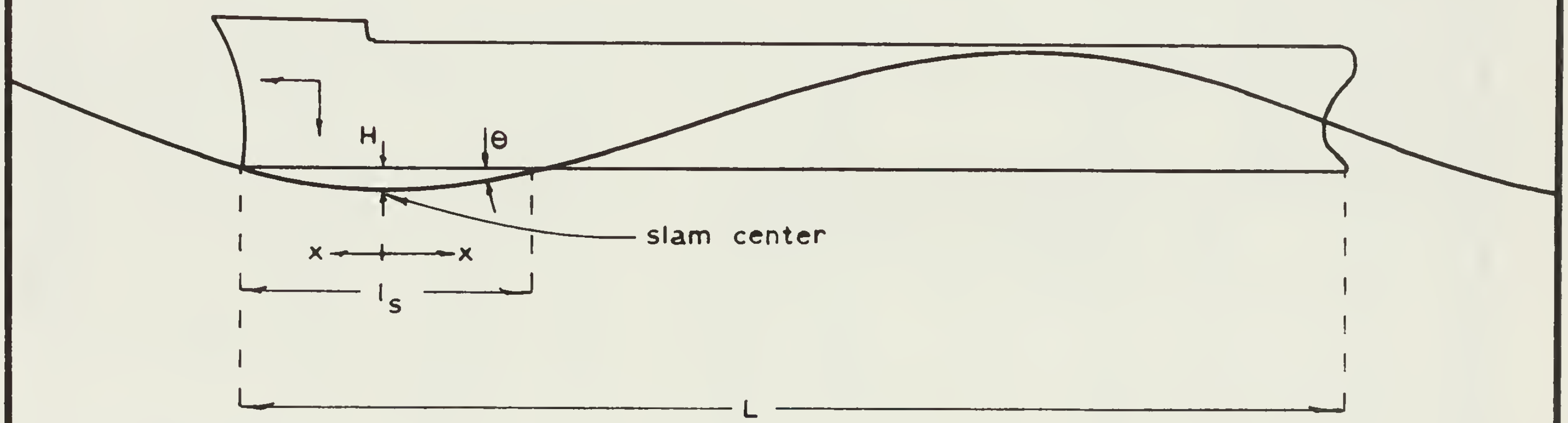

FIGURE 6 - MODEL OF SLAM

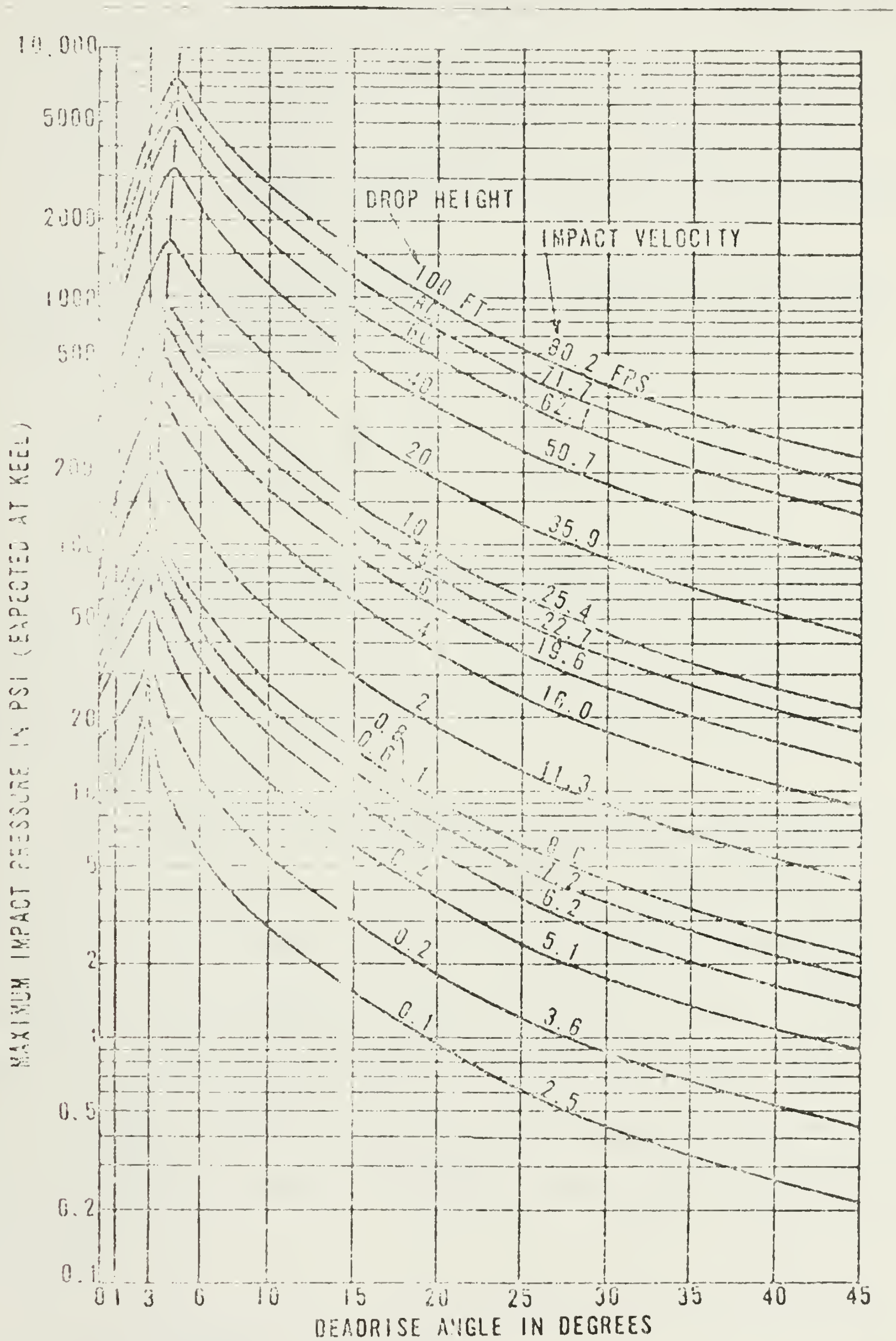

FIGURE 7 - MAXIMUM SLAM PRESSURE vs. DEADRISE ANGLE

$$\hat{p}_n(\alpha,\theta) = \hat{p}_n(\alpha)\ 10^{-0.12\ |\theta|} \tag{15}$$

where $\hat{p}_n(\alpha,\theta)$ = maximum keel pressure with angular correction

$\hat{p}_n(\alpha)$ = pressure predicted by equation (12)

θ = angle between the keel and wave surface in degrees

If the wave is assumed approximately sinusoidal the wave slope can be calculated as

$$\theta = 935.\ \overline{H(1/3)}\ X\ /\ L^2 \tag{16}$$

where X = distance away from the slam center in feet

Using equations (15) and (16) the most probable or the extreme pressure for design may be modified to allow for other than zero impact angle.

The peak pressures do not occur at the same time along the length of the ship. From full scale measurements on the Wolverine State and model tests [14], it was determined that the pressure pulse traveled from forward to aft or vice versa at speeds from 260 to 520 fps for a 520 ft ship. Ochi assumes that the slowest traveling velocity is the worst slam condition and that the results can be Froude scaled for different length ships to get

$$v_t = 260\ \sqrt{L/520}\ = 11.4\ \sqrt{L} \tag{17}$$

where v_t = traveling velocity in feet per second

This assumption was not felt valid since the traveling velocity should increase as the rate of entrance into the water increased--that is, as relative velocity increased so should the traveling velocity. It is agreed that if a slam could occur at the highest possible relative velocity and the slowest traveling velocity it would be the worst case, but it is felt that these two conditions cannot be met at the same time.

The traveling velocity is calculated using the slam model in Figure 6. Using this model, the height above the water surface at the slam center, the most probable or extreme relative velocities of the slam center, and the length of the slam area are known or can be found. From this information the traveling velocity is given by

$$v_t = l_s/2t_t \tag{17a}$$

where l_s = slam length from FP to aft extent of slam

t_t = time slam takes to travel from aft extent of slam to slam center

and

$$t_t = H/VEL \tag{17b}$$

where H = height of slam center above the wave surface at start of slam

VEL = most probable or extreme relative velocity of the slam center

The last information required before integration can proceed is the spatial distribution of pressure along the girth. The most probable and the extreme pressure for design as calculated by equations (10) and (12) and modified with equation (15) for wave slope are only valid at the keel. Following again Ochi's work [14], [18], the maximum slam pressure can be assumed constant along the flat bottom of the hull. From the end of the flat the pressure drops off approximately linearly to zero at the 1/10 design draft, T'. Figure 8a shows this for a typical section. The pressure component of interest is the vertical component on the hull. The values in Figure 8a must be multiplied by COSβ where β is defined as the angle between the normal and the vertical at the point in question. Figure 8b shows the new vertical component of the pressure distribution needed to find the slam force.

All the information is now available to calculate the slam force and impulse. The procedure is as follows:

1. Using equations (4) and (5) along with the r.m.s. relative motions and velocities from tables [15], calculate the number of slams at each station. The last station aft with $N(t) \geq 1$ is the longitudinal extent of slam.
2. Calculate the most probable extreme pressure from equation (10) or the extreme pressure for design from equation (12) at each station forward of the last slam station as found above.

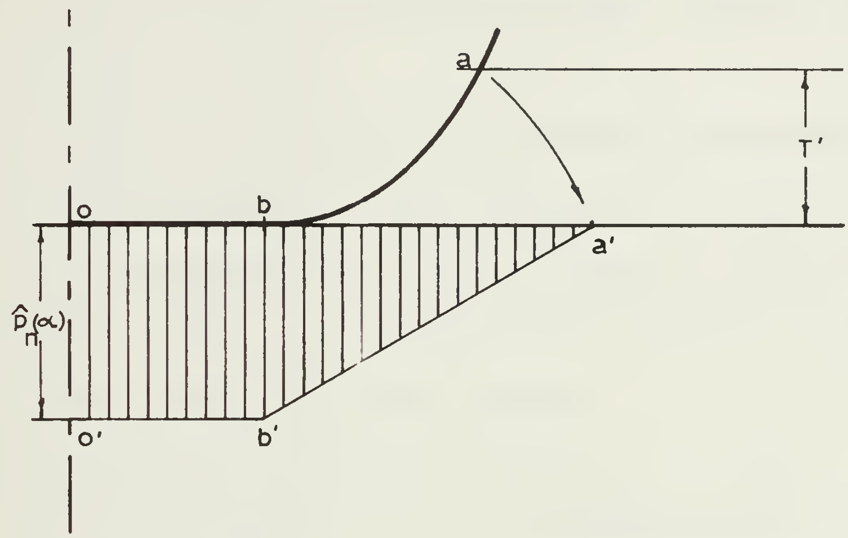

FIGURE 8a - GIRTH PRESSURE DISTRIBUTION

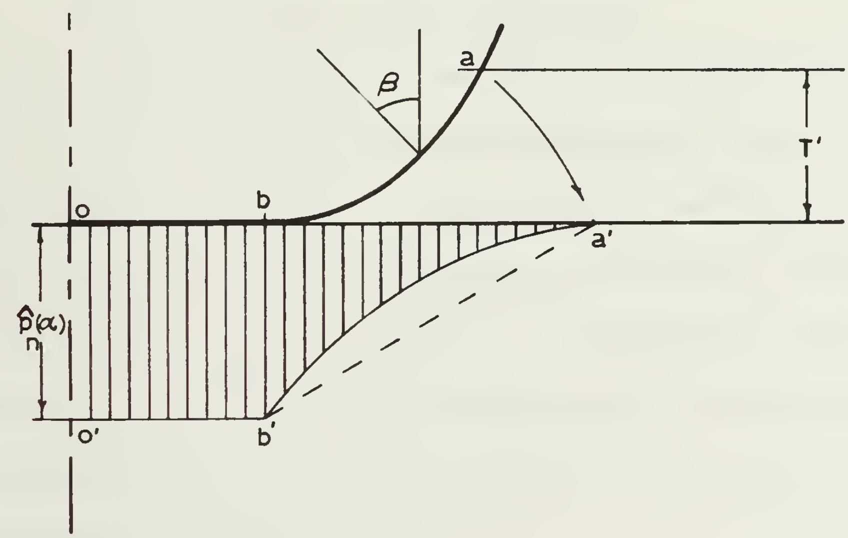

FIGURE 8b - DISTRIBUTION OF VERTICAL PRESSURE

3. Assuming the center of slam is midway between the FP and the last station where slamming occurs, calculate the slopes using equation (16) and the corrected pressures at each station using equation (15).
4. Calculate the vertical pressure components at each station for approximately 10 waterlines between the baseline and T' as in Figure 8. The spatial distribution of the vertical pressure is now known over the entire slam region.
5. Assuming a triangular shape as in Figure 5, and a pulse duration of t_1 as predicted by either equation (13) or (14), add temporally at each location. The start of slam pressure rise (t_i) at each spatial point is predicted by equation (17a) in the longitudinal direction and by the relative velocity in the girth direction.

Due to the numerical integration procedure necessary, a computer program was written to perform the above calculations and numerical integrations. The program and the details of the above procedure are discussed in the next section.

By evaluating the pressures at different time increments, the force time history can be determined for each section. Integrating these force histories over time will give the slam impulse at each station.

V. COMPUTER PROGRAM AND DISCUSSION OF RESULTS

A computer program was written to implement the procedure discussed in Section IV. A listing of the program is included as Appendix B. There are many input and output options which are discussed in Appendix C which is designed to be a user's manual. A short example program illustrating the data deck and some of the possible outputs is included as Appendix D. In this section the results obtained from the program will be discussed using the Mariner and Fotini-L as example ships.

Throughout this thesis stations are numbered from 0 at the forward perpendicular to 20 at the after perpendicular. Since slamming occurs in the forward portion of the ship where the lines change rapidly, half-stations were introduced numbered from 0 to 40 similarly. The slam forces calculated are considered as centered at the half-stations extending equal distances forward and aft of these half-stations.

Two computer programs were written and used. The assumptions and calculations of Reference [14] were duplicated and used to compare with the results in this work. The only deviations were the use of equation (6a) for $k > 0.19$ and the use of seakeeping information obtained from the Reference [15] tables. The results for the Mariner were identical to those obtained by Ochi [14]. The significant aspect of this is that good results were obtained without recourse to seakeeping computer programs.

OPERATING CONDITIONS

The Mariner was used as one of the example ships and the computer program was run under various operating conditions. The four conditions selected for discussion here are:

1.	MARINER	FULLY LOADED	7.4 KNOTS
2.	MARINER	FULLY LOADED	15.5 KNOTS
3.	MARINER	LIGHT DRAFT	15.5 KNOTS
4.	MARINER	LIGHT DRAFT	7.4 KNOTS

all at a significant wave height of 25 feet. Table 1a lists the ship characteristics for the two loading conditions considered. This ship and conditions were chosen since they were used in Reference [14].

MARINER	FULLY LOADED	LIGHT DRAFT
BLOCK COEF. (C_B)	0.613	0.583
L/B	6.95	6.95
B/T	2.82	3.80
DRAFT FWD.	27 FEET	16.4 FEET
DRAFT AFT.	27 "	23.6 "
$\overline{H(1/3)}$	25 "	25 "
LBP	528 "	528 "
BEAM (B)	76 "	76 "
DESIGN DRAFT	29.75 "	29.75 "

TABLE 1a - MARINER OPERATING CONDITIONS AND DIMENSIONS

A second ship, the FOTINI-L, was analyzed and is one of the three ships reported on in Reference [4]. The principal characteristics and loading conditions are given in Table 1b.

FOTINI-L	FULLY LOADED	BALLAST
BLOCK COEF. C_B	0.84	0.65
L/B	7.55	7.55
B/T	2.79	3.55
DRAFT FWD.	38.0 FEET	28.31 FEET
DRAFT AFT.	38.0 "	31.46 "
$\overline{H(1/3)}$	20 to 40 FEET	20 to 40 FEET
LBP	800 FEET	800 FEET
BEAM	106 "	106 "
DESIGN DRAFT	38.0 "	38.0 "
SPEED (KNOTS)	9.59, 14.38	9.59, 14.38

TABLE 1b - FOTINI-L OPERATING CONDITIONS AND DIMENSIONS

R.M.S. RELATIVE MOTIONS AND VELOCITIES

The first modification to the Ochi-Motter approach was to apply a broadness factor correction to the r.m.s. relative motion and velocity. If the ship responses are assumed to be narrow band processes, the r.m.s. values of the responses can be obtained directly from the tables. These tabular results do not take into account the fact that seakeeping processes are not ideally narrow band [15]. More realistic values can be obtained if a broadness factor correction is applied:

$$m_o' = m_o \; (1 - \varepsilon^2/2) \tag{18}$$

where m_o = r.m.s. value of response from tables

m_o' = corrected r.m.s. value

ε = broadness factor

and

$$\varepsilon^2 = 1 - \frac{m_2^2}{m_o m_4} \tag{19}$$

where m_k = the k^{th} moment of the spectrum.

A value of $\varepsilon = 0.59$ is used in the calculations [7], [15]. This correction factor reduces the relative motions and velocities and therefore reduces the slam forces predicted.

RESULTS USING OCHI-MOTTER METHOD

The results for the four operating conditions using the Ochi-Motter method with the broadness factor correction are given in Tables 2 to 5 and Figures 9 to 12. These results are for each of the half-stations where slamming is predicted. Table 6 shows the total slam impulse and the amplitude and duration of an equivalent slam for the ship. Table 6 results are presented for ease of comparison of the two methods.

HALF STATION	FORM COEF (K)	REL MOTION: REL VELOCITY (NON-DIM)	EXT PRESSURE: MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.024 0.074	33.0 19.2	187.	141.	8.9	86.	0.161	0.000
2	0.055	0.023 0.070	66.7 37.7	108.	567.	35.8	349.	0.161	0.050
3	0.065	0.021 0.066	67.3 36.5	56.	681.	43.4	423.	0.161	0.099
4	0.074	0.020 0.062	63.8 32.7	25.	737.	48.0	441.	0.171	0.149
5	0.093	0.018 0.058	64.7 30.3	9.	941.	61.0	560.	0.171	0.198
6	0.115	0.017 0.055	62.2 25.0	3.	1102.	72.1	624.	0.181	0.248

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 2 - 1-MARINER - OCHI METHOD

HALF STATION	FORM COEF (K)	REL MOTION: REL VELOCITY (NON-DIM)	EXT PRESSURE: MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.029 0.099	65.5 41.1	1008.	281.	17.6	182.	0.151	0.000
2	0.055	0.028 0.095	138.8 85.2	754.	1191.	74.4	773.	0.151	0.050
3	0.065	0.027 0.091	146.2 88.6	538.	1504.	94.3	983.	0.151	0.099
4	0.074	0.025 0.086	146.5 87.2	361.	1757.	110.4	1147.	0.151	0.149
5	0.093	0.024 0.082	160.4 93.0	224.	2397.	151.4	1573.	0.151	0.198
6	0.115	0.022 0.078	170.8 95.8	127.	3137.	198.2	1931.	0.161	0.248
7	0.139	0.021 0.073	173.8 93.2	63.	4006.	253.5	2470.	0.161	0.298
8	0.157	0.019 0.069	161.4 80.7	27.	4481.	284.0	2766.	0.161	0.347
9	0.176	0.018 0.065	143.4 63.9	9.	4792.	306.9	2814.	0.171	0.397
10	0.186	0.016 0.060	113.1 40.3	2.	4263.	275.6	2527.	0.171	0.447

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 3 - 2-MARINER - OCHI METHOD

HALF STATION	FORM COEF (K)	REL MOTION: REL VELOCITY (NON-DIM)	EXT PRESSURE: MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.026 0.091	60.9 40.2	2937.	262.	16.3	170.	0.151	0.000
2	0.055	0.025 0.087	127.7 83.9	2366.	1097.	68.5	712.	0.151	0.050
3	0.065	0.024 0.083	135.7 88.1	1827.	1396.	87.5	910.	0.151	0.099
4	0.074	0.022 0.078	135.4 87.7	1338.	1611.	102.0	1060.	0.151	0.149
5	0.093	0.021 0.074	149.4 95.0	915.	2233.	141.1	1466.	0.151	0.198
6	0.115	0.019 0.070	160.1 100.2	572.	2939.	185.7	1809.	0.161	0.248
7	0.139	0.018 0.065	164.4 100.7	317.	3777.	239.8	2336.	0.161	0.298
8	0.157	0.016 0.061	154.7 91.7	149.	4294.	272.1	2651.	0.161	0.347
9	0.176	0.015 0.057	140.1 79.2	56.	4683.	299.9	2750.	0.171	0.397
10	0.186	0.013 0.052	114.2 59.4	15.	4304.	278.3	2552.	0.171	0.447
11	0.166	0.012 0.048	73.4 32.2	2.	3217.	209.5	1814.	0.181	0.496

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 4 - 3-MARINER - OCHI METHOD

HALF STATION	FORM COEF (K)	REL MOTION: REL VELOCITY (NON-DIM)	EXT PRESSURE: MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.022 0.069	33.5 21.7	998.	143.	9.0	88.	0.161	0.000
2	0.055	0.021 0.065	68.2 43.4	657.	579.	36.6	356.	0.161	0.050
3	0.065	0.019 0.061	69.4 43.3	391.	701.	44.7	436.	0.161	0.099
4	0.074	0.018 0.057	66.3 40.6	203.	778.	49.9	486.	0.161	0.149
5	0.093	0.016 0.053	68.1 40.5	88.	991.	64.3	589.	0.171	0.198
6	0.115	0.015 0.048	67.2 38.1	29.	1193.	77.9	714.	0.171	0.248
7	0.139	0.013 0.044	61.6 32.3	7.	1365.	89.9	778.	0.181	0.298

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 5 - 4-MARINER - OCHI METHOD

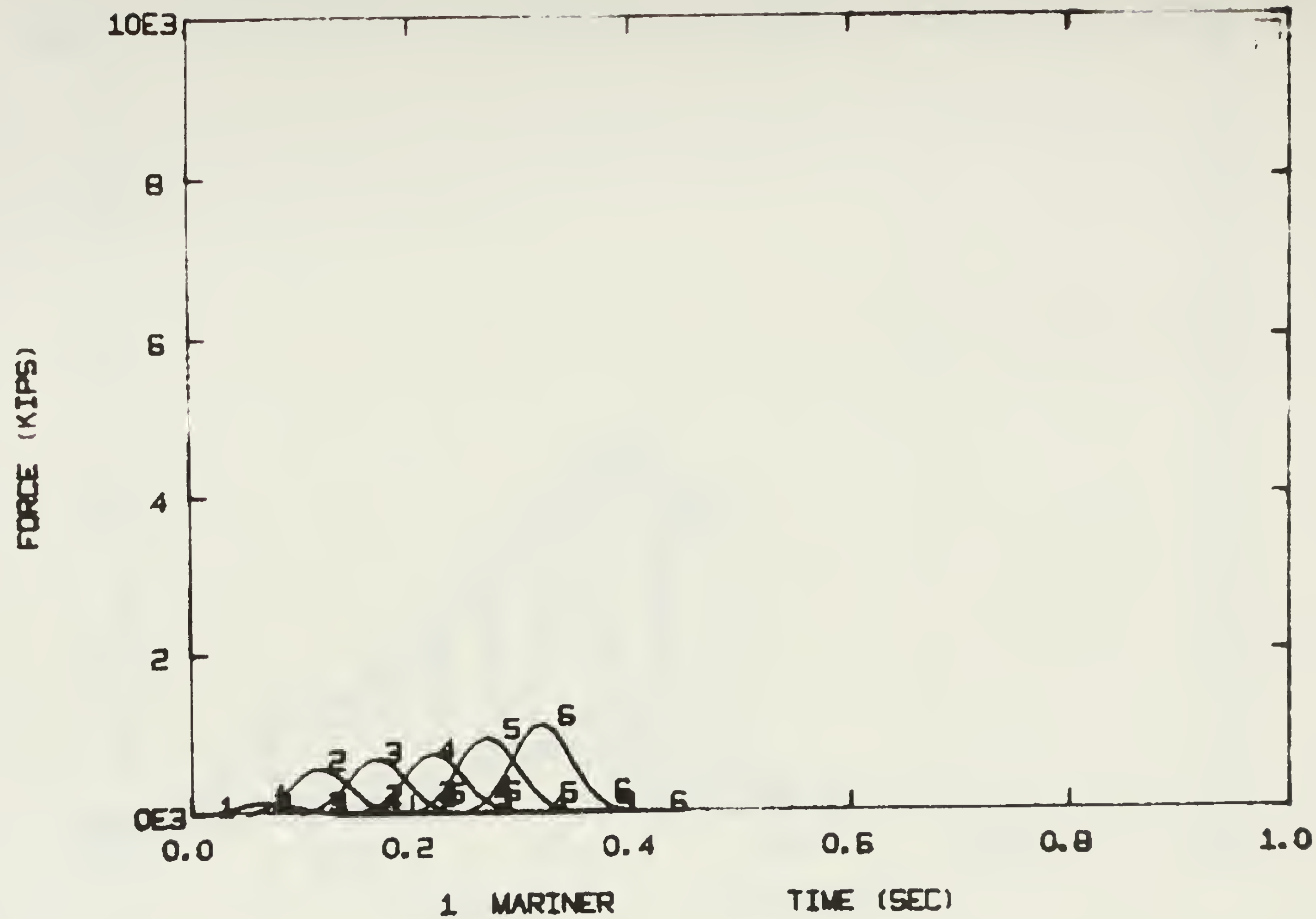

FIGURE 9 - 1-MARINER - OCHI MODEL

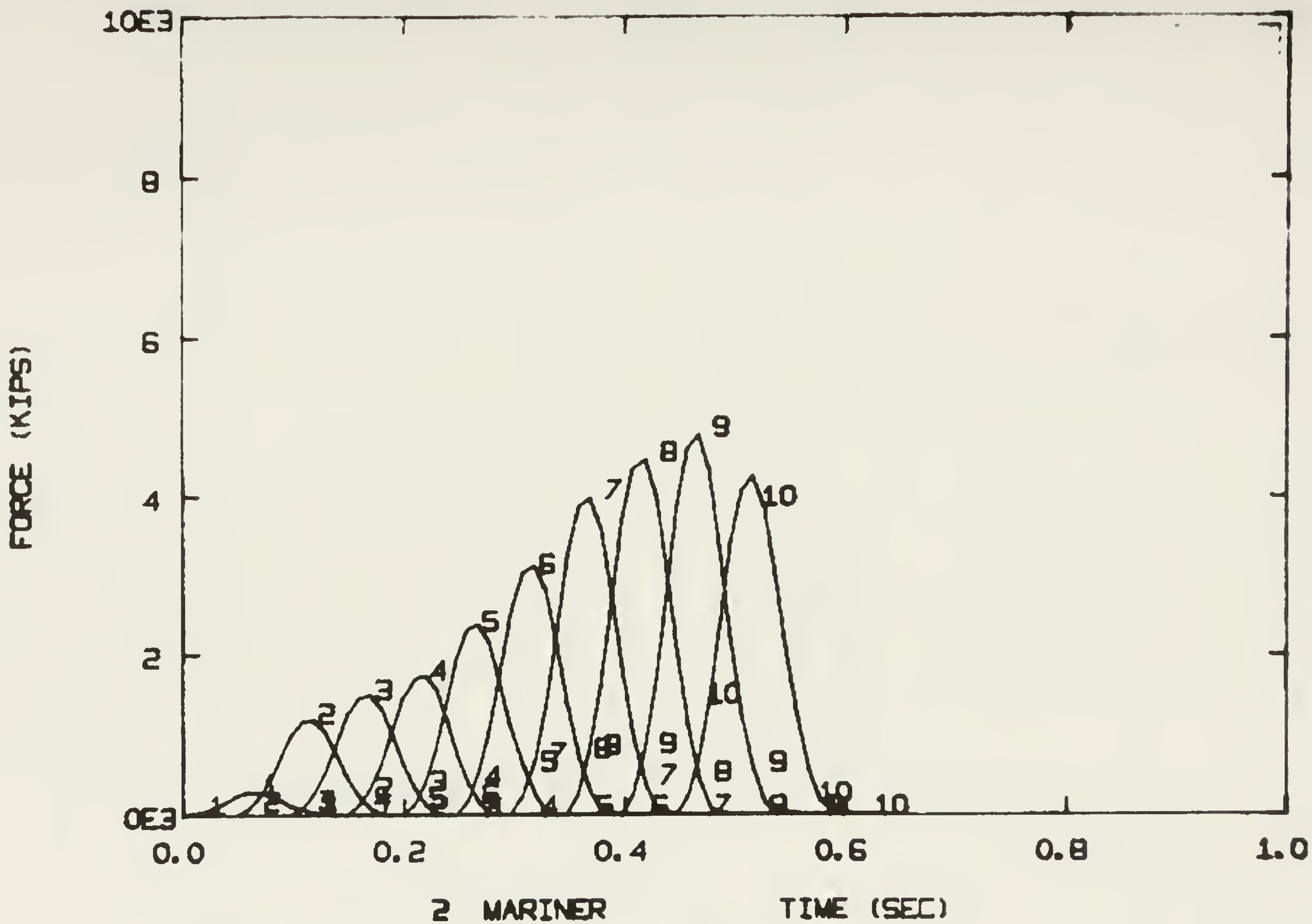

FIGURE 10 - 2-MARINER - OCHI MODEL

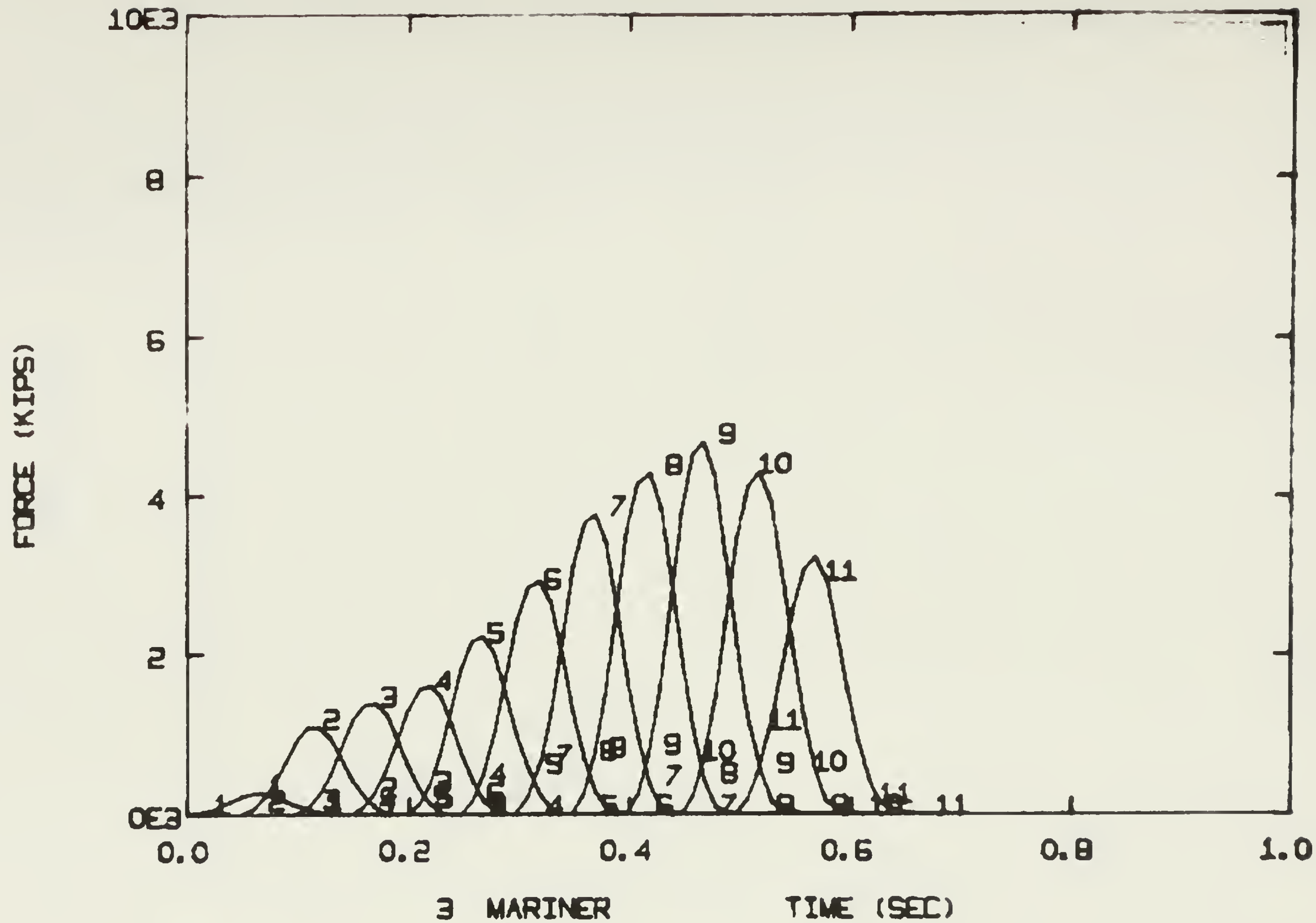

FIGURE 11 - 3-MARINER - OCHI MODEL

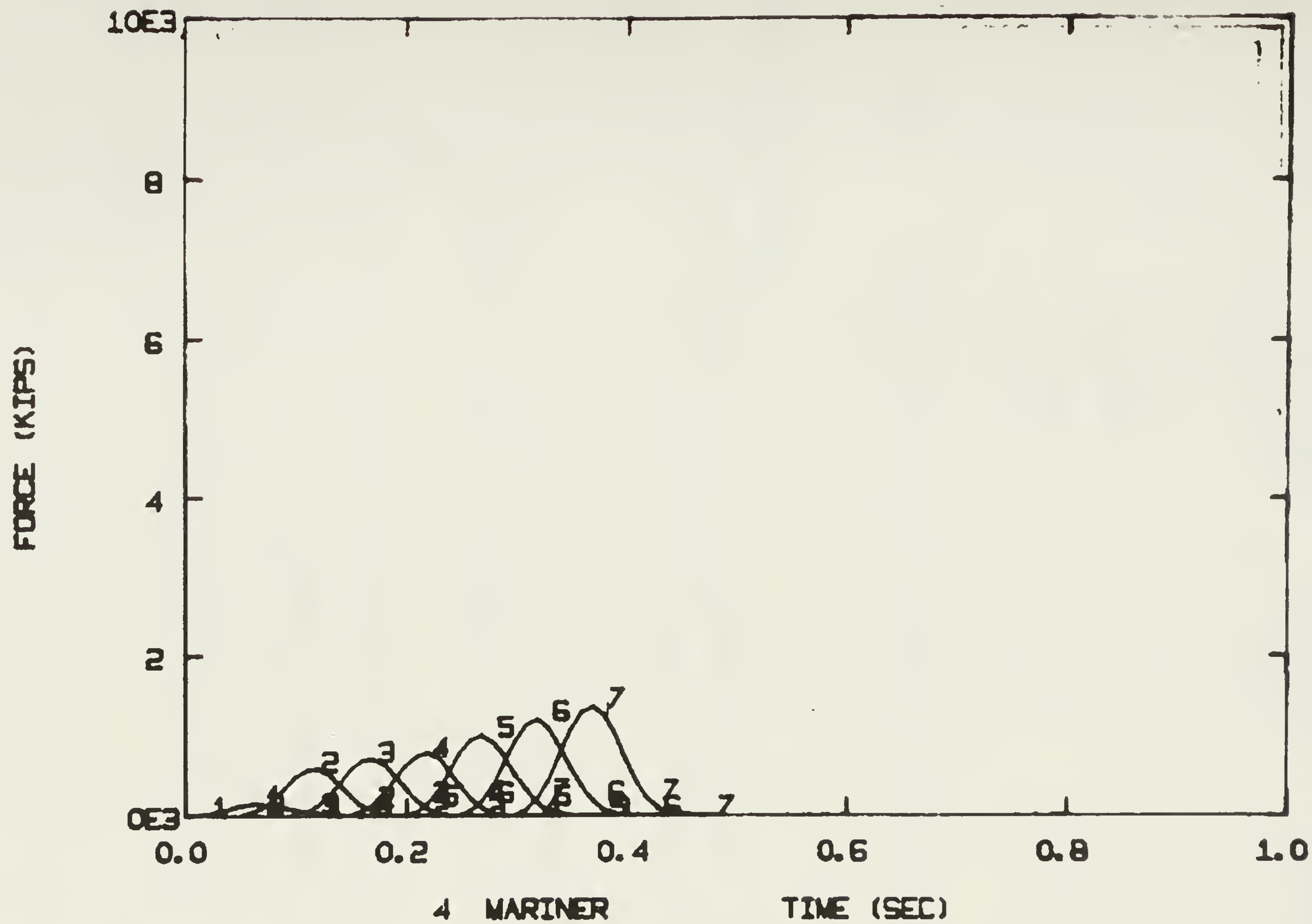

FIGURE 12 - 4-MARINER - OCHI MODEL

MARINER CONDITION	TOTAL SINE FORCE AMPLITUDE (KIPS)	APPROX. DURATION (SEC)	TOTAL IMPULSE (KIP-SEC)
1	985	0.43	269
2	4490	0.62	1766
3	4406	0.68	1901
4	1220	0.48	372

TABLE 6 - TOTAL SLAM FORCE AND IMPULSE (OCHI METHOD)

NEW METHOD RESULTS

The changes made to the Ochi method discussed in the previous sections and incorporated into the second computer program are:

1. an angular correction applied as per equation (15),
2. a different model of slamming as shown in Figure 6, and
3. a traveling velocity calculated by equation (17a).

The results for the same four operating conditions are given in Tables 7 to 10 and Figures 13 to 16. Table 11 gives the total values of slam force and impulse corresponding to Table 6 above.

HALF STATION	FORM COEF (K)	REL MOTION REL VELOCITY (NON-DIM)	EXT PRESSURE MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.024 0.074	13.4 7.8	176.	69.	3.6	43.	0.131	0.000
2	0.055	0.023 0.070	36.6 20.5	102.	375.	19.5	234.	0.131	0.013
3	0.065	0.021 0.066	49.7 26.8	53.	602.	31.8	382.	0.131	0.026
4	0.074	0.020 0.062	63.4 32.3	24.	852.	47.6	530.	0.141	0.038
5	0.093	0.018 0.058	47.6 22.2	9.	812.	44.8	499.	0.141	0.026
6	0.115	0.017 0.055	34.0 13.5	3.	711.	39.2	408.	0.151	0.013

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 7 - 1-MARINER - NEW METHOD

HALF STATION	FORM COFF (K)	REL MOTION REL VELOCITY (NON-DIM)	EXT PRESSURE MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.029 0.099	14.7 9.2	950.	77.	3.9	51.	0.121	0.000
2	0.055	0.028 0.095	41.8 25.6	711.	438.	22.3	289.	0.121	0.016
3	0.065	0.027 0.091	59.5 35.9	507.	742.	38.1	495.	0.121	0.032
4	0.074	0.025 0.086	80.4 47.6	340.	1164.	60.2	782.	0.121	0.047
5	0.093	0.024 0.082	118.3 68.3	212.	2116.	111.1	1443.	0.121	0.063
6	0.115	0.022 0.078	169.7 94.9	120.	3741.	195.7	2347.	0.131	0.079
7	0.139	0.021 0.073	128.2 68.4	60.	3557.	185.8	2228.	0.131	0.063
8	0.157	0.019 0.069	88.3 43.9	25.	2957.	154.4	1851.	0.131	0.047
9	0.176	0.018 0.065	58.2 25.7	9.	2324.	123.8	1378.	0.141	0.032
10	0.186	0.016 0.060	34.0 11.9	2.	1517.	82.4	918.	0.141	0.016

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 8 - 2-MARINER - NEW METHOD

HALF STATION	FORM COEF (K)	REL MOTION REL VELOCITY (NON-DIM)	EXT PRESSURE MOST FROM PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.026 0.091	13.7 9.0	2769.	72.	3.6	47.	0.121	0.000
2	0.055	0.025 0.087	38.7 25.3	2230.	405.	20.6	268.	0.121	0.018
3	0.065	0.024 0.083	55.5 35.7	1723.	691.	35.5	461.	0.121	0.036
4	0.074	0.022 0.078	74.6 48.0	1262.	1057.	55.9	726.	0.121	0.053
5	0.093	0.021 0.074	110.2 70.0	863.	1970.	103.4	1344.	0.121	0.071
6	0.115	0.019 0.070	159.4 99.4	539.	3515.	183.9	2205.	0.131	0.089
7	0.139	0.018 0.065	121.7 74.1	299.	3367.	176.4	2116.	0.131	0.071
8	0.157	0.016 0.061	84.7 50.0	141.	2838.	148.2	1777.	0.131	0.053
9	0.176	0.015 0.057	56.9 32.0	53.	2274.	121.1	1349.	0.141	0.036
10	0.186	0.013 0.052	34.4 17.8	14.	1544.	83.4	928.	0.141	0.018
11	0.224	0.012 0.048	22.1 9.6	2.	1157.	62.7	652.	0.151	0.000

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 9 - 3-MARINER - NEW METHOD

HALF STATION	FORM COEF (K)	REL MOTION: REL VELOCITY (NON-DIM)	EXT PRESSURE: MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.022 0.069	13.7 8.8	941.	71.	3.6	44.	0.131	0.000
2	0.055	0.021 0.065	37.5 23.7	610.	386.	20.0	240.	0.131	0.015
3	0.065	0.019 0.061	51.2 31.9	360.	620.	32.8	393.	0.131	0.029
4	0.074	0.018 0.057	65.8 40.2	192.	921.	49.3	592.	0.131	0.044
5	0.093	0.016 0.053	50.3 29.8	83.	856.	47.3	526.	0.141	0.029
6	0.115	0.015 0.048	36.8 20.8	27.	772.	42.5	473.	0.141	0.015
7	0.139	0.013 0.044	25.0 13.1	6.	657.	36.3	377.	0.151	0.000

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

TABLE 10 - 4-MARINER - NEW METHOD

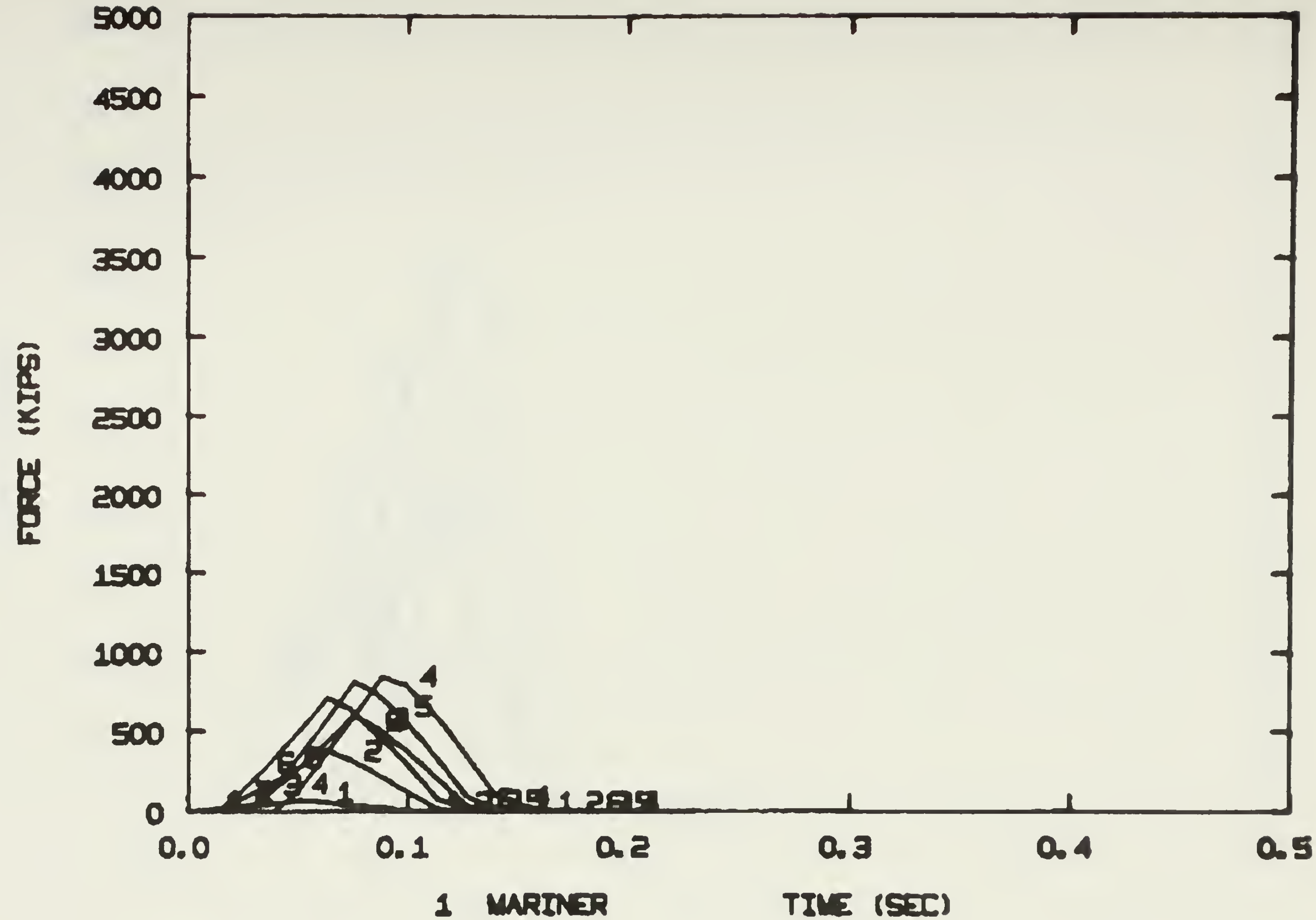

FIGURE 13 - 1-MARINER - NEW MODEL

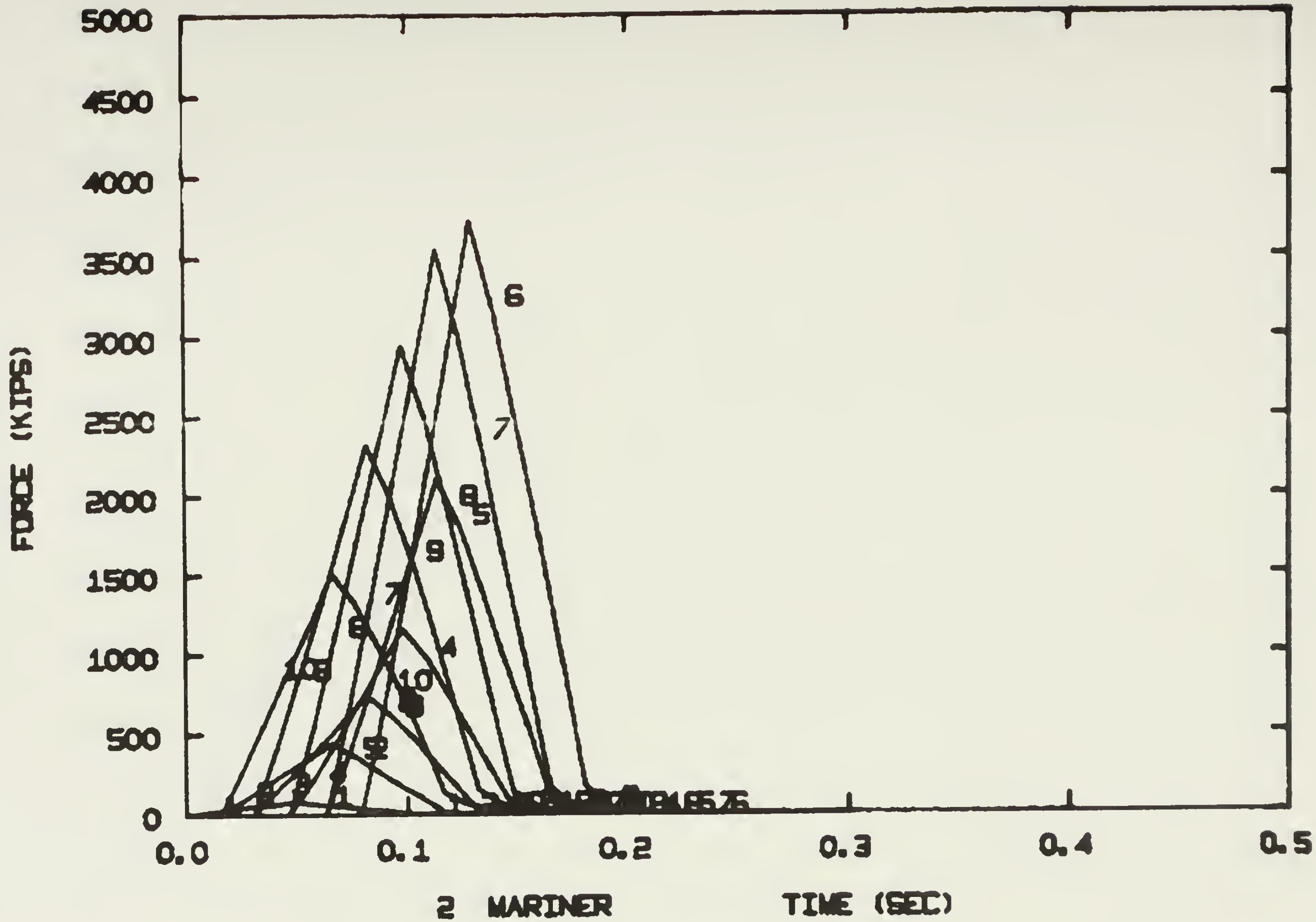

FIGURE 14 - 2-MARINER - NEW MODEL

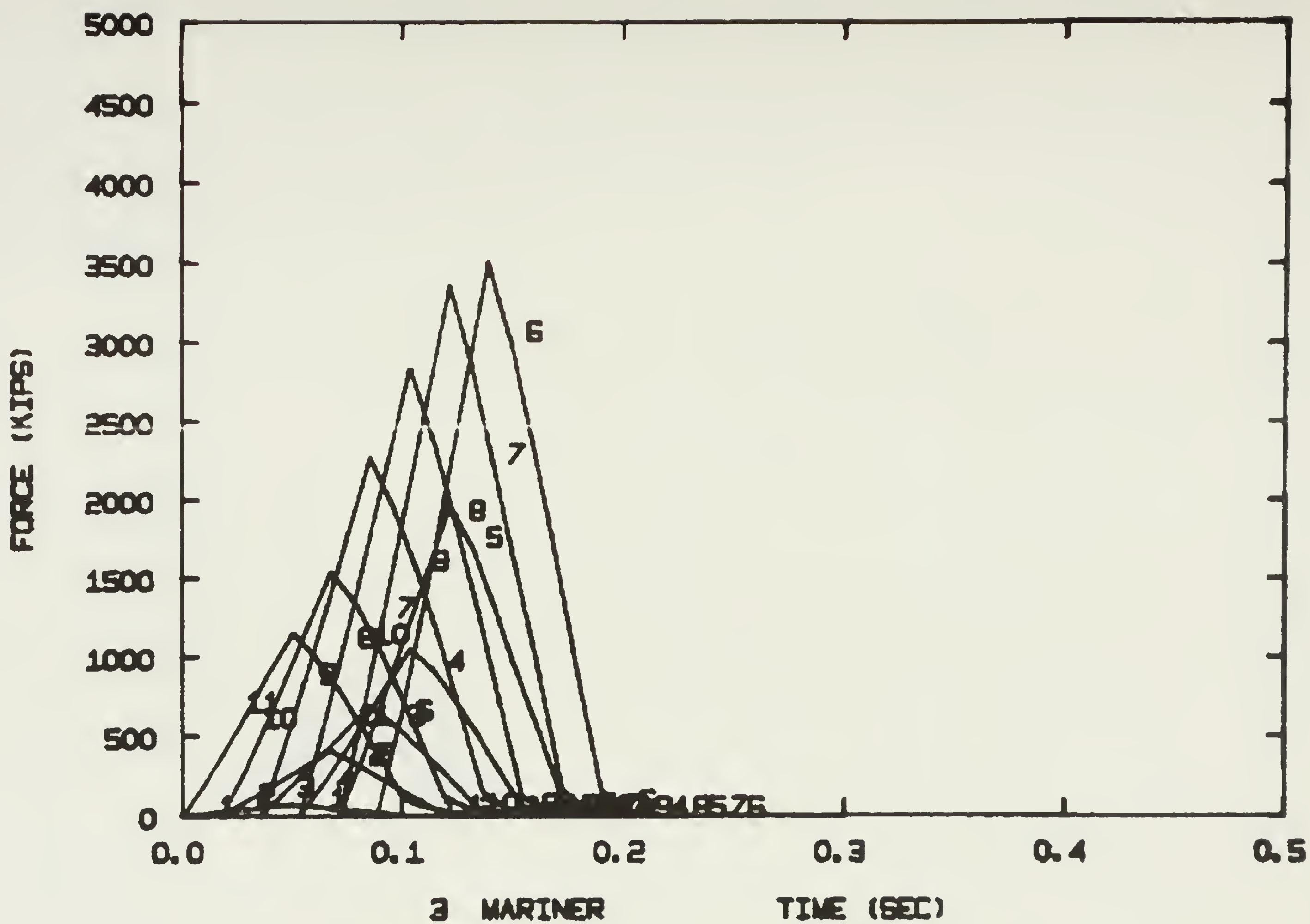

FIGURE 15 - 3-MARINER - NEW MODEL

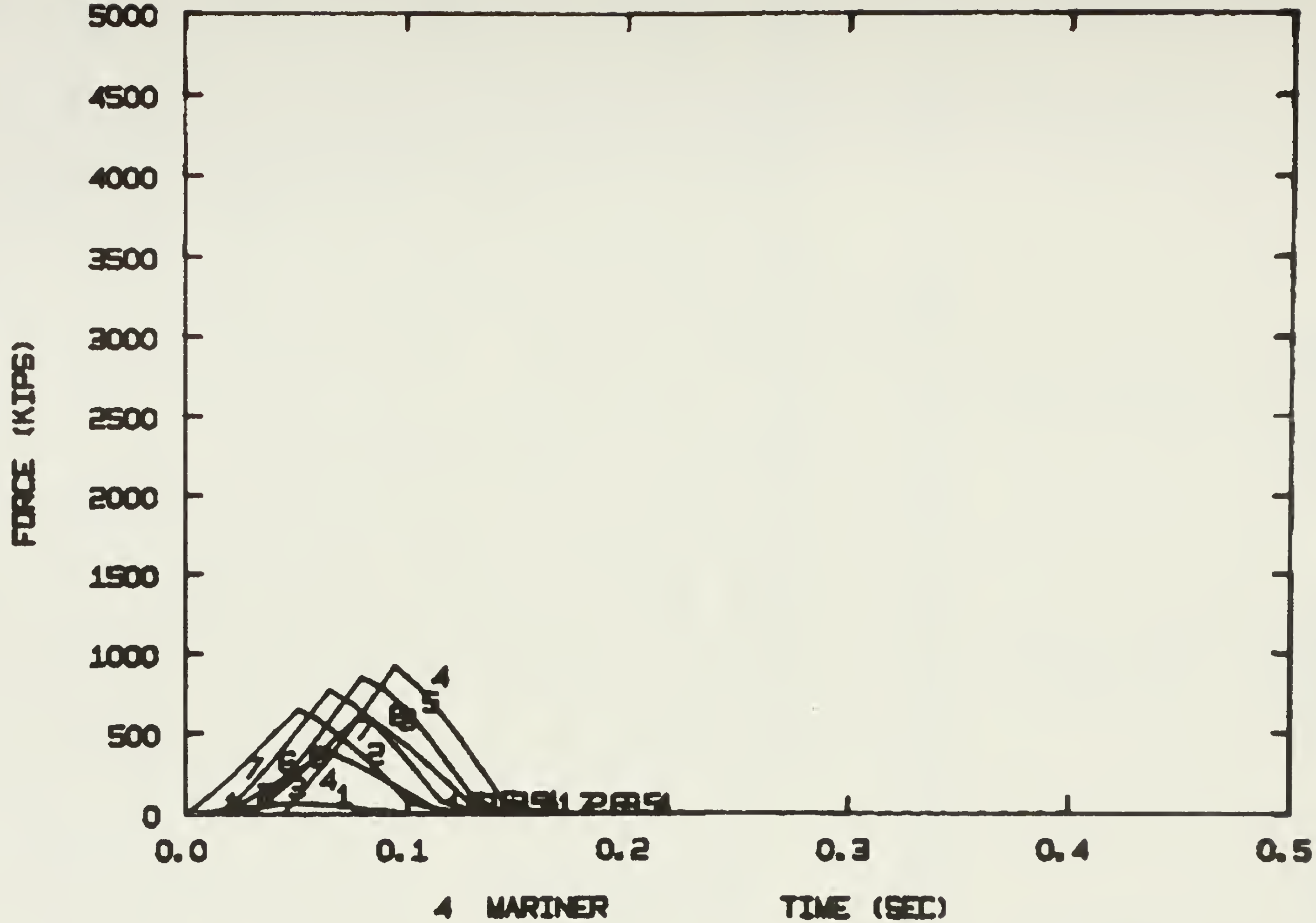

FIGURE 16 - 4-MARINER - NEW MODEL

MARINER CONDITION	TOTAL SINE FORCE AMPLITUDE (KIPS)	APPROX. DURATION (SEC)	TOTAL IMPULSE (KIP-SEC)
1	1632	0.18	187
2	7312	0.21	978
3	7105	0.22	995
4	2084	0.17	232

TABLE 11 - TOTAL SLAM FORCE AND IMPULSE (NEW MODEL)

COMPARISON OF RESULTS BETWEEN THE TWO METHODS

In general the new model predicts lower slam impulses, shorter slam durations and higher slam forces. In addition, the time histories are more triangular in the new model.

The lower slam impulses are a result of the angular correction term only. If the correction were not used, both methods would yield the same impulse values.

The shorter total duration is a result of the slam model and the calculated traveling velocity. The model reduces the duration by approximately 1/2 since the pressure wave travels forward and aft toward the slam center. An additional decrease in slam duration occurs because the calculated traveling velocities are, in general, higher than those calculated by Ochi. For these four operating conditions the traveling velocities range from 731 fps for case 3 to 1016 fps for case 1.

The total force on the ship is the spatial and temporal integration of the local pressures. In the new method the pressures are always less than or equal to the Ochi method but the new method yields larger forces. This is due to the integration over time. Referring to the plots of both methods, Figures 10 and 14, the reason for this can be seen. The half-station forces are more bunched together in the new method. The total force on the ship at any time is the sum of the forces on each half-station at the same time. Due to the greater overlap in the new method, more half-stations are summed at the same time, resulting in higher forces.

The importance of the various parameters of storm duration, threshold velocity, local slam duration, significant wave height, and most probable vs. extreme pressure for design were looked at to determine the sensitivity of the results to their variation.

SENSITIVITY TO STORM DURATION

To determine how important accurate prediction of the maximum storm duration was, the MARINER case 2 was run for different values of storm duration with all other input variables held constant. As seen in Figure 17 the total slam impulse is not sensitive to storm duration. A 50% increase in storm duration from 30 to 45 hours results only in a 4% increase in slam impulse.

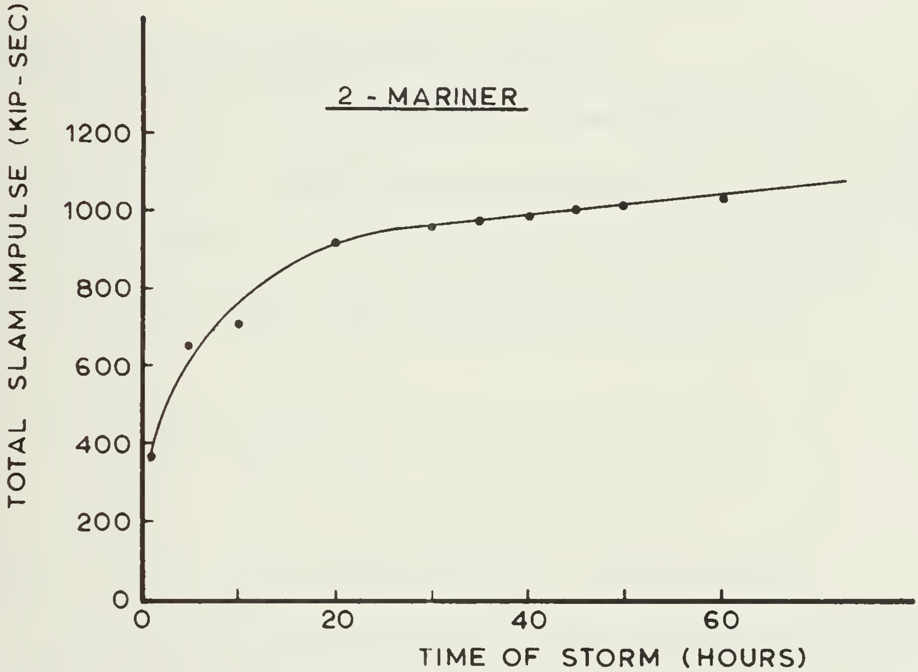

FIGURE 17 - TOTAL SLAM IMPULSE vs. TIME OF STORM

SENSITIVITY TO THRESHOLD VELOCITY

Since the threshold velocity at which slamming occurs has been defined differently by various authors, the sensitivity of slam impulse to changes in threshold velocity was determined. Values of threshold velocity between 6 and 20 ft/sec were used for MARINER case 2 and the total slam impulse plotted against threshold velocity in Figure 18. From this figure it can be seen that the use of 12 ft/sec is reasonable and, at worst, conservative.

SENSITIVITY TO LOCAL SLAM DURATION

The total slam impulse on the ship is the sum of all the local impulses. Those parameters which affect local impulse also influence the total impulse the same amount. From Figure 5 the local slam impulse is given by:

$$I_\ell = 1/2\ \hat{p}_n(\alpha)\ t_1 \tag{20}$$

where I_ℓ = local impulse/in^2 = lb-sec/in^2

From (20) it can be seen that a large variation in t_1 results in a large change in I_ℓ and subsequently in the total impulse. Therefore total slam impulse is very sensitive to the local slam duration. Since the determination of t_1 is in question, this is considered the area where further work is necessary (Appendix A).

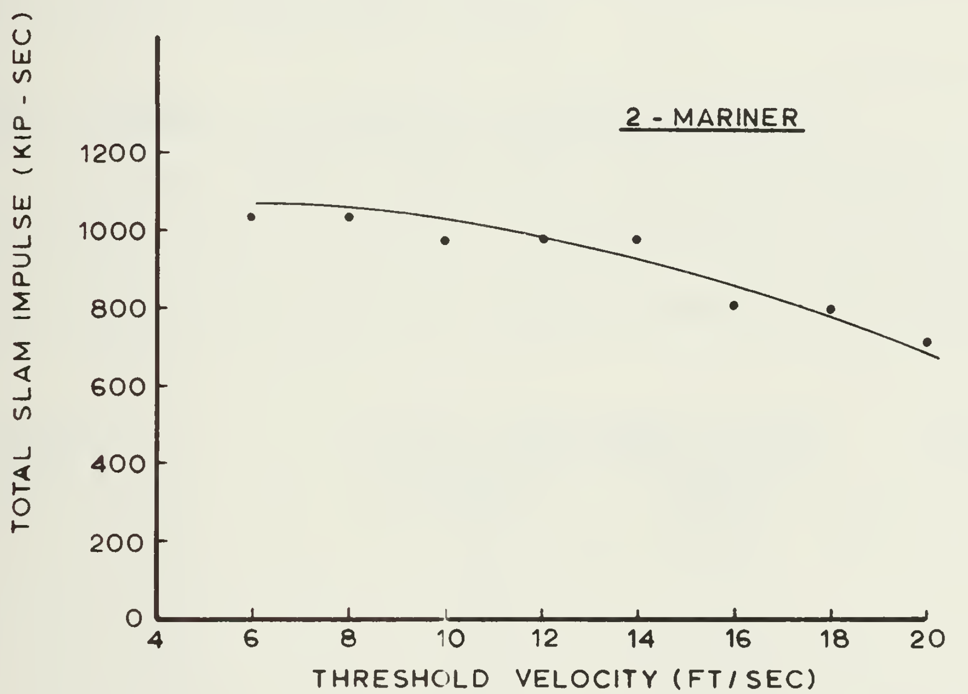

FIGURE 18 - TOTAL SLAM IMPULSE vs. THRESHOLD VELOCITY

AFFECT OF SIGNIFICANT WAVE HEIGHT

Another ship, the Fotini-L, was also analyzed. Several computer runs were made using both programs varying the significant wave height from 12 to 40 feet. Figure 19 is a plot of the results. The Ochi method gives results approximately 2 1/2 times the new model results. As expected, the impulse increases with significant wave height and with velocity in the seaway. The rate of increase decreases at higher significant wave heights and is expected since the ship responses behave similarly at higher sea states.

MOST PROBABLE vs. EXTREME PRESSURE FOR DESIGN

The four Mariner cases were run using the new method for the most probable extreme pressure and the extreme pressure for design cases. Tables 11 and 12 summarize the results.

MARINER CONDITION	TOTAL SINE FORCE AMPLITUDE (KIPS)	APPROX. DURATION (SEC)	TOTAL IMPULSE (KIP-SEC)
1	733	0.20	91
2	3248	0.25	510
3	3663	0.25	591
4	1147	0.19	137

TABLE 12 - TOTAL SLAM FORCE AND IMPULSE (MOST PROBABLE EXTREME PRESSURE USED)

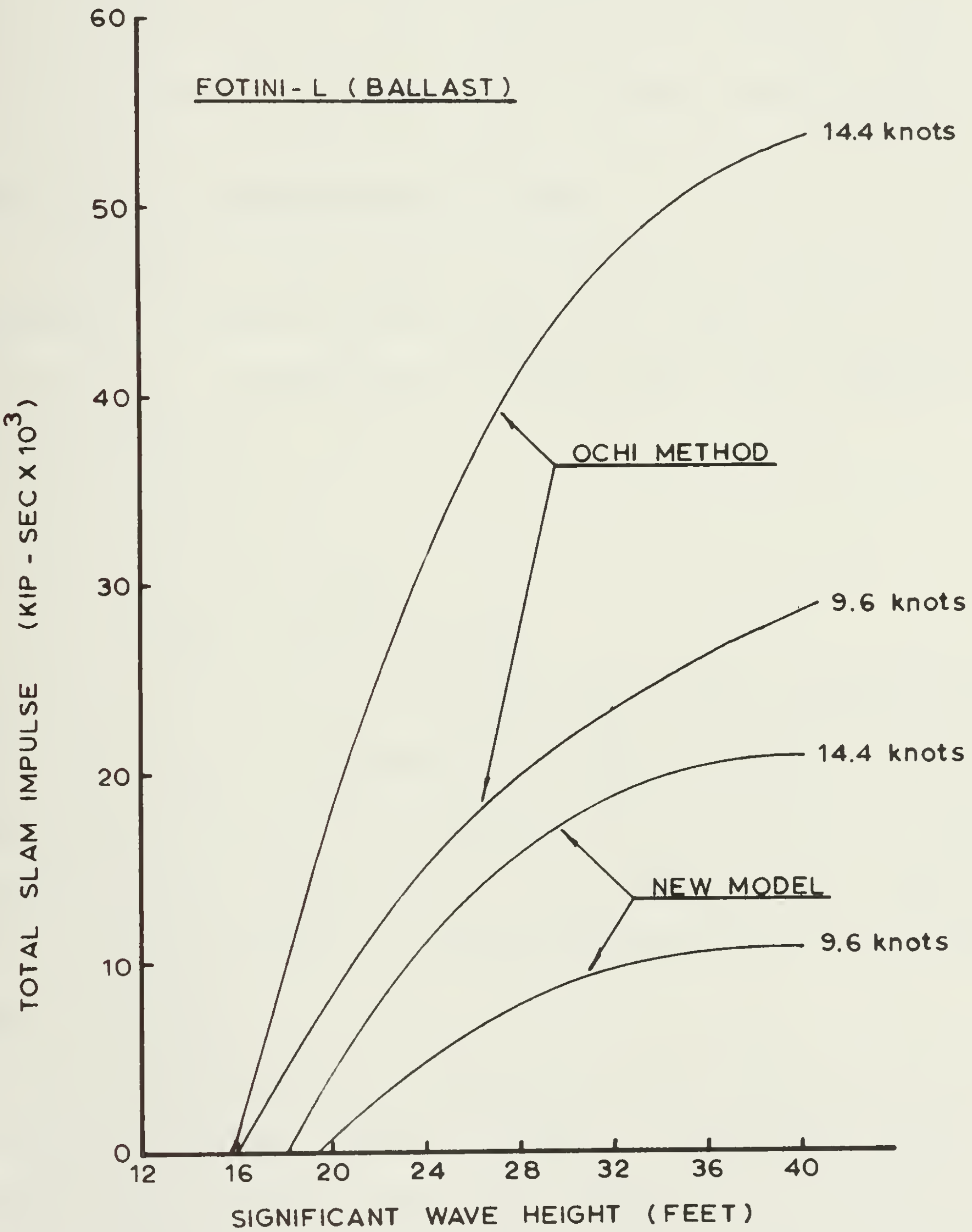

FIGURE 19 - SLAM IMPULSE vs. SIGNIFICANT WAVE HEIGHT

The duration of the slam is greater in the most probable case since a lower relative velocity predicted results in a slower traveling velocity (n.b., Table 11). The impulses are approximately 1/2 those obtained from the extreme pressure for design calculations. Since the most probable extreme value is indicative of the largest value observed in a trial, these values should be used if any comparison is done with full scale data.

SHAPE OF THE SLAM FORCING FUNCTION

Knowledge of the shape of the slam forcing function is necessary to input the slam force into the S.H.V.R.S. program. The S.H.V.R.S. program will accept three input shapes for the forcing function:

1. triangular
2. half-sine wave
3. damped half-sine wave.

The forcing function can be applied at each of the half-stations with time delays corresponding to the traveling velocity or a single slam force can be applied at one location. Since much of the previous work [2], [3], [4] used a single sine pulse, this program develops a half-sine approximation to compare with these results.

The shape of the force at each half-station is different in the Ochi method and this method. In the Ochi method the assumed shape of the local slam (Figure 5) is not critical. Several pulses of different shapes were tried in the Ochi

program but the predicted half-station forcing functions were about the same. This is because the traveling velocity is slow enough that the slam starts at different times along the length of the half-station. In the new method the traveling velocity is, in general, high enough that the slam starts at the same time along the entire half-section. This results in a force shape the same as the assumed local slam pulse. The shape of the slam force at each half-station (Figures 9 to 12) in the Ochi method can be approximated as half-sine functions. The program calculates the amplitude and duration of these approximations. The shape of the force at each half-station (Figures 13 to 16) in the new method can be assumed triangular, of height equal to the maximum force, and of duration

$$t_2 = 1.1\ t_1 = 4.8 \times 10^{-3}\ \sqrt{L} \tag{21}$$

where t_2 was determined by neglecting the "tails" of the force function and maintaining the same impulse.

The total slam force shape can be obtained by adding the forces from each half-station at the same time. Figure 20 is a plot of the total slam force for the MARINER case 2, time of storm 30 hours, calculated by the new program. Figure 21 is the plot of the forcing function at each half-station. If the points which are less than 1% of the maximum value are neglected and a linear regression analysis done on the remaining points in Figure 20, the triangle formed is almost equilateral. Therefore this shape should be used for the total slam forcing function.

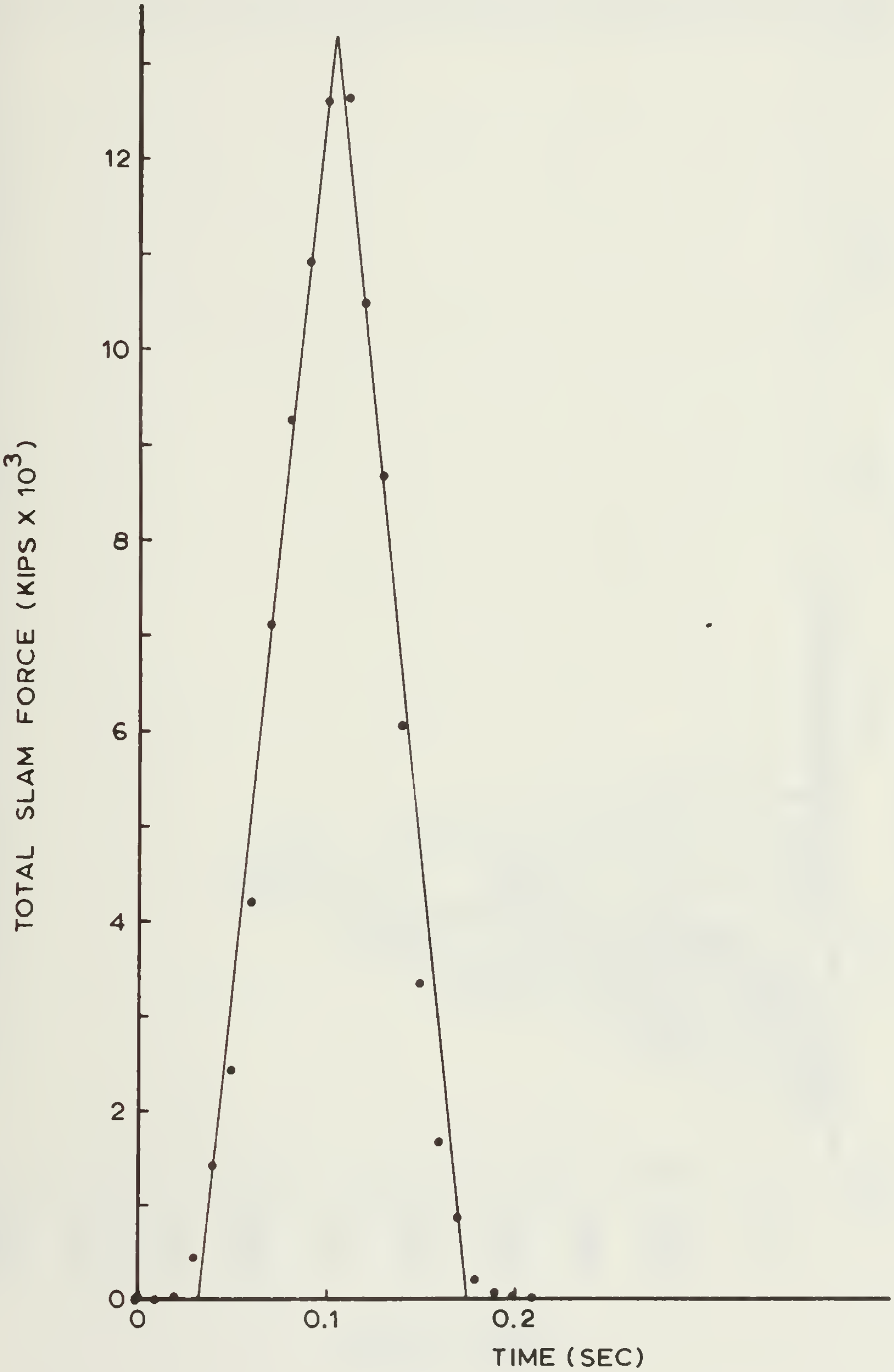

FIGURE 20 - TOTAL SLAM FORCE vs. TIME

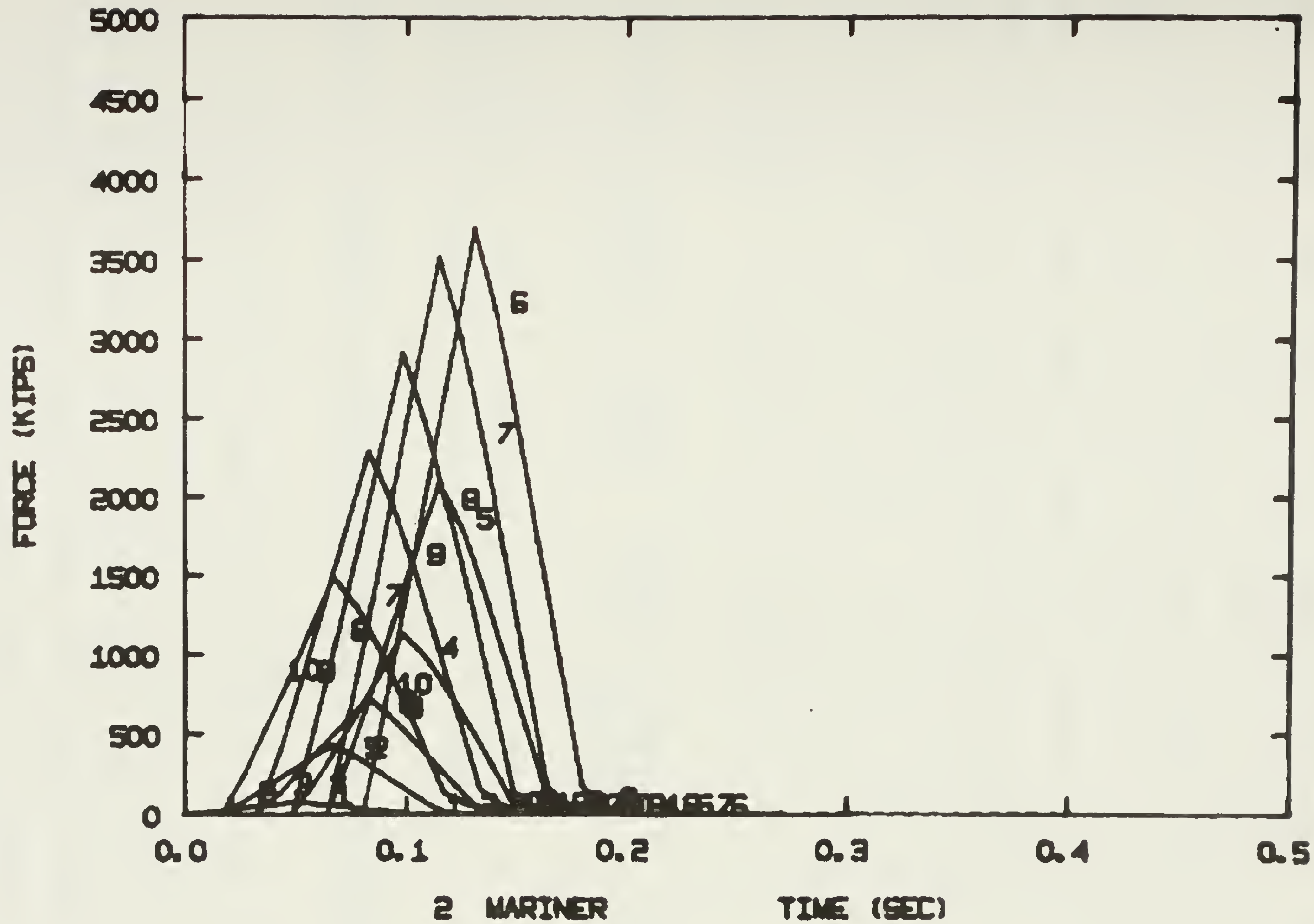

FIGURE 21 - 2-MARINER - NEW MODEL - TSTORM = 30 hours

MIDSHIP SLAM BENDING MOMENT AND STRESS

The FOTINI-L was considered at different significant wave heights, velocities, and loading conditions. The results for the total slam impulse in the ballast condition are shown in Figure 19. As the significant wave height and/or ship speed is increased, the slam center moves aft. Donovan [4] determined midship bending moment and stress for the FOTINI-L using a 100 ton-sec half-sine slam impulse, applied 36 feet aft of the forward perpendicular. This slam location is close to half-station 2 of this model. From the computer runs on the FOTINI-L, two operating conditions resulted in slam centers at half-station 2. These are given in Table 13.

CONDITION	LOADING CONDITION	SPEED (KNOTS)	$\overline{H(1/3)}$ (FEET)	TOTAL IMPULSE (KIP-SEC)	DURATION OF IMPULSE (SEC)
1-FOTINI-L	FULL	14.38	32	1199	0.18
2-FOTINI-L	BALLAST	9.59	20	960	0.18

TABLE 13 - FOTINI-L - SLAMS PREDICTED AT HALF-STATION 2

From the graphs of response in Donovan's work, these slam impulses give the moments and stresses in Table 14 for various stiffnesses. This is determined assuming a linear relationship between bending moment and impulse which holds if the slam durations are the same--that is, holding all else constant, doubling the slam impulse doubles the bending moment response.

		STIFFNESS*				
	CONDITION	60%	80%	100%	120%	140%
BENDING MOMENT (FT-TONS)	1-FOTINI-L	343	364	375	391	404
	2-FOTINI-L	246	268	283	296	313
STRESS (KPSI)	1-FOTINI-L	26.5	22.1	18.9	16.5	14.5
	2-FOTINI-L	21.9	19.2	16.7	14.5	13.1

TABLE 14 - FOTINI-L - BENDING MOMENT AND STRESS AMIDSHIPS DUE TO SLAMS CENTERED AT HALF-STATION 2

*The stiffnesses are % of as built values.

The values in Table 14 for the fully loaded case are approximately 5.4 times what was predicted in Reference [4] and 4.3 times the predicted results in the ballast condition.

VI. RECOMMENDATIONS FOR FUTURE WORK

As seen by the values of stress obtained in Table 14, the slam forces and impulses result in large midship stresses on the FOTINI-L. The stresses could be evaluated only for slams at half-station 2 since dynamic response results were available only at this station. As the slam center moves aft, the total slam impulse and force increases. Higher slam stresses could result from slams at different locations. Therefore additional slam locations should be considered in the S.H.V.R.S. program in any study of the slam response.

The shape of the total slam force is more triangular than sine (n.b., Figure 20). The S.H.V.R.S. program should be run for several triangular pulses and the results compared to the half-sine results available. If they do not come close, a triangular pulse should be used.

The validity of using a single total force approximation vice distributed forces along the bottom needs to be verified. The results of this work give the distributed forces as well as a half-sine approximation for the total slam force. Both should be run on the S.H.V.R.S. program to determine if the two agree. If they do not, either the distributed forces should be used or a new approximation developed which does agree.

Although the slam impulses are less in this method than in the Ochi method, they still result in large slam stresses. There is still reason to believe, because of these large

values, that these impulse values are also overpredicted. As discussed earlier, and in Appendix A, equation (13) for the duration of the local slam pulse is in question. There presently exists a large amount of literature on drop tests but few model and full scale results are available to determine durations. Correlation with full scale data needs to be accomplished to determine if equation (13) is valid or something like equation (14) would be better.

A series of model tests should be run to verify that the model of slamming used here is valid. This would include verifying or modifying the traveling velocity calculations and the correction equation for the angle between the keel and the wave surface (equation (15)).

VII. CONCLUSION

The work presented here develops a slam force prediction method which is sensitive to seakeeping parameters based on a model of slamming different from other methods developed to date. The results obtained show slam impulses and time durations less than those in the Ochi-Motter method [14], but impulses greater than the 100 ton-sec value used by Kline [3]. It is felt that values closer to those predicted here should be used in the overall A.B.S. study on hull stiffness. As a minimum, the results of this work have shown that the 100 ton-sec value used in the work to date is in question and should not be applied to all ships under every operating condition.

REFERENCES

1. Sellers, M.L. and Kline, R.G., "Some Aspects of Ship Stiffness", S.N.A.M.E., 1967.

2. Evans, J.H. and Kline, R.G., "First Progress Report on the Hull Girder Stiffness Criteria", unpublished report, May 10, 1975.

3. Kline, R.G., and Daidola, J.C., "Hull Flexibility Criteria Study", SSC-249, 1975.

4. Donovan, M.R., "A Study of the Relation Between Ship Stiffness and Maximum Slamming Moments Amidships", Masters Degree Thesis, M.I.T., September 1975.

5. Oakley, O.H., "An Analytical and Experimental Study for Prediction of Ship Impact Forces in a Seaway", M.I.T., O.E. Report No. 69-6, August 1969.

6. Tick, L.J., "Certain Probabilities Associated With Bow Submergence and Ship Slamming in Irregular Seas", Journal of Ship Research, Vol. 2, No. 1, June 1958.

7. Loukakis, T.A., "Computer Aided Prediction of Seakeeping Performance in Ship Design", M.I.T., Department of Naval Architecture and Marine Engineering, Report No. 70-3, August 1970.

8. Chuang, S.L., "Experimental Investigation of Flat Bottom Body Slamming", Journal of Ship Research, Vol. 10, No. 1, March 1966.

9. Chuang, S.L., "Investigation of Impact of Rigid and Elastic Bodies with Water", Naval Ship Research and Development Center, Report No. 3248, February 1970.

10. Szebehely, V.G., "On Slamming", D.T.M.B. Report No. 995, January 1956.

11. Leibowitz, R.C., "Comparison of Theory and Experiment for Slamming of a Dutch Destroyer", D.T.M.B. Report No. 1511, June 1962.

12. d'Oliviera, J.M., "Wave Induced Bending Moment Due to Ship Slamming", M.I.T. Ocean Engineer Thesis, May 1973.

13. Mansour, A. and d'Oliviera, J.M., "Hull Bending Moment Due to Ship Bottom Slamming in Regular Waves", Journal of Ship Research, Vol. 19, No. 2, June 1975.

14. Ochi, M.K. and Motter, L.E., "Prediction of Slamming Characteristics and Hull Responses for Ship Design", S.N.A.M.E. Transactions, Vol. 81, 1973.

15. Loukakis, T.A. and Chryssostomidis, C., "Seakeeping Standard Series for Cruiser-Stern Ships", S.N.A.M.E. N.Y. Section, Paper No. 4, November 1975.

16. Ochi, M.K. and Motter, L.E., "A Method to Estimate Slamming Characteristics for Ship Design", Marine Technology, Vol. 8, No. 2, April 1971.

17. Ochi, M.D. and Bonilla-Norat, J., "Pressure Velocity Relationship in Impact of a Ship Model Dropped onto the Water Surface and in Slamming Waves", Naval Ship Research and Development Center, Report No. 3153, June 1970.

18. Ochi, M.K., "Model Experiments on Ship Strength and Slamming in Regular Waves", S.N.A.M.E. N.Y. Section, Paper No. 4, November 1958.

19. Jasper, N.H. and Birmingham, J.T., "Sea Tests of the USCGC UNIMAC Part I - General Outline of Tests and Test Results", D.T.M.B. Report No. 967, March 1956.

20. Chuang, S.L., "Slamming of Rigid Wedge - Shaped Bodied With Various Deadrise Angles", D.T.M.B. Report No. 2268, October 1966.

21. Gerlach, C.R., "Investigation of Water Impact of Blunt Rigid Bodies - Size Scale Effects", Southwest Research Institute, Report No. 2, SWRI Project No. 02-2036, November 1, 1968.

APPENDIX A - LOCAL SLAM PRESSURE, DURATION OF PULSE

Ochi predicts that the slam pulse is triangular and the duration is 0.1 seconds for a 520 foot ship. From this he Froude sacles and concludes that equation (13) holds - i.e.,

$$t_1 = 4.4 \times 10^{-3} \sqrt{L}$$

From full scale measurements on the USCGC UNIMAC [19], L = 300 feet, values of slam duration locally were of the order of 0.020 to 0.025 seconds. Using equation (13), this length ship results in a predicted duration of t_1 = 0.076 seconds. This discrepancy was too great to ignore without further consideration.

From drop tests done by Chuang [8], [9], and [20], on flat bottom impact with zero deadrise angle, the following equation holds for deadrise angles less than 3°

$$t_1 = 4\ l_o/C_{air} \tag{22a}$$

where

l_o = half-width of infinitely long flat plate

C_{air} = speed of sound in air = 1125 ft/sec

For the UNIMAC and the durations of slams measured this would predict the half-width at frame 23 to be of the order of 6 feet. Lines were not available to determine how close

this agrees to the half-breadth of the 1/10 draft at this section, but it is a reasonable value for a ship with beam 41 ft.

In other drop test data [21] equation (22a) held quite well for many different sized test specimens if the beam was used as the scaling parameter. Without more information from full scale tests, equation (22a) cannot be verified and therefore will not be used. It is felt that the local half-breadth should be the scaling parameter, not the length as used by Ochi.

It is proposed here that

$$t_1 = 3.6 \times 10^{-3} B' \tag{14}$$

which comes from equation (22a) would be a better estimate of slam duration with possible modification of the constant from full scale data.

Equation (22a) holds for small deadrise angles less than 3° where the compressibility of air influences the duration of pressure pulse. For larger angles the impact pressure time history becomes more steep fronted with about half the duration predicted by equations (22a) and (14). Therefore above 3° equation (22b) holds fairly well.

$$t_1 = 2\, l_o/C_{air} \tag{22b}$$

Although equations (22a) and (22b) are for deadrise angles, a similar result might be expected for angles between the keel and the wave surface. Therefore equation (22a) is probably valid in the flat region near the slam center while equation (22b) is probably valid outside this region.

For the MARINER equation (14) yields values of $t_1 = 0.022$ at half-station 4 to $t_1 = 0.115$ at half-station 16. Therefore it results in much lower impulses than would result using equation (13). For the FOTINI-L larger values were found using equation (14) than from equation (13). At half-stations 4 and 10, $t_1 = 0.130$ and 0.189 respectively using (14). This would result in larger impulses than one would get if (13) were used. If equation (22b) were applied in the appropriate regions, the above resulting impulses could be reduced.

Use of equations (22a), (22b), and (14) are not justified at this time, but it is felt that full scale data should be analyzed to determine if equations of this form are valid. If they are, further reduction of calculated impulses by the program is possible in many ship cases.

APPENDIX B - COMPUTER PROGRAM LISTING

This appendix contains a listing of the FORTRAN computer program. It was written for an Interdata Model 70 computer and requires approximately 60 K of memory. Two subroutines are called which are not listed here but are readily available to most users as part of the IBM Scientific Subroutine Package.

```
C       PROGRAM SLAMCW                              WALKER      JANUARY 1976
C       PROGRAM  MAIN ---  THIS PROGRAM CALCULATES THE SLAM FORCES AND
C       IMPULSES GENERATED ON A SHIP IN AN IRREGULAR SEA
        DIMENSION XIN(5),YIN(5),XOUT(11),YOUT(11),XX(17,11),YY(11),T(20),
      C          VK(17),YO(11),RM(17),PV(17),EPRES(17),PROBPR(17),
      C            PRES(17,11),FORCE(17,20),DVEL(17),TIME(17)
        DIMENSION A(17),DUR(17),SLAMS(17),TM(20),SHAPF(17),
      CPRSLAM(17),FMAX(17),AIMPLS(17),PVEL(17),XG(17,11),XSCL(4)
        DATA ESL,ESP,NIN,NOUT,PI/99.,99.,5,11,3.141592654/
        DATA N,M/8,5/
        DATA SHAPE/0.89375,0.7916667,0.69375,0.6,0.5104167,0.425,0.3475,
      C0.266666,0.19375,0.125,0.16041666,0.00,-0.05625,-0.108333,-0.15625
      C,-0.2,-0.239583/
    1   READ (N,1000) IO1,IO2,IO4,IO8
 1000   FORMAT (7I5)
        IF (IO2.LT.1) GO TO 999
C       READ SHIP NAME AND LOADING CONDITION
        READ (N,1001) (T(I),I=1,20)
 1001   FORMAT (20A4)
C       READ SHIP DATA CONSTANT IN PROBLEM
        READ (N,1002) BB,HH,ALBP,ALWL,STASP
 1002   FORMAT (5F10.5)
        WRITE (M,1003)
 1003   FORMAT ('1',35X,'THIS PROGRAM CALCULATES THE SLAM FORCE DISTRIBUTI
      CON VS TIME',/,38X,'ON THE LOWER 1/10 OF THE SHIP FROM STATION 8 FO
      CRWARD.',////)
C       WRITE SHIP NAME AND DATA
        WRITE (M,1004) (T(I),I=1,20),BB,HH,ALBP,ALWL,STASP
 1004   FORMAT (20X,20A4,//,30X,'HALF BEAM = ',F10.5,10X,'DESIGN DRAFT = '
      C,F10.5,//,30X,'LBP = ',F10.2,16X,'LENGTH LOAD WATER LINE = ',F10.2
      C,//,30X,'DISTANCE BETWEEN STATIONS = ',F6.2,40X,//,35X,'(ALL DISTA
      CNCES IN FEET)',////)
C       CALCULATE THE K VALUES USING SUBROUTINE SPOO
        H=HH/10.
        S=HH/100.
        XOUT(1)=0.0
        DO 10 I=2,11
        XOUT(I)=XOUT(I-1) + S
   10   YY(I)=XOUT(I)
        I=0
C       READ OFFSETS AT ANY 5 WATERLINES
        READ (N,1005) (XIN(J),J=1,5)
 1005   FORMAT (5F10.5)
   20   READ (N,1005) (YIN(J),J=1,5)
        I=I+1
        IF (YIN(5).LE.0.5) GO TO 30
C
C       CALCULATE OFFSETS IN 10 INCREMENTS FROM B.L. TO 1/10 DESIGN DRAFT
C       USING SUBROUTINE UGLYDK
C
        CALL UGLYDK (NIN,NOUT,XIN,YIN,XOUT,YOUT,ESL,ESR)
        DO 21 J=1,11
        JJ=12-J
        YO(J)=YOUT(JJ)
   21   XX(I,J)=YOUT(J)
        B=YOUT(11)
        IAOP=IO1
C       CALCULATE THE FORM COEF. OF THIS STATION
        CALL SPOO (YO,VKK,B,H,S,BB,HH,IAOP,I)
```

```
      VK(I)=VKK
      IF (I04.LT.1) GO TO 20
      D=FLOAT(I)/2.
      WRITE (M,1006) D,(YIN(J),XIN(J),YOUT(J),XOUT(J),J=1,5),(YOUT(J),
     C            XOUT(J),J=6,11)
 1006 FORMAT ('1',49X,50('*'),/,50X,'*',48X,'*',/,50X,'*',11X,'STATION',
     CF5.1,'  OFFSETS (FEET)', 9X,'*',/,50X,'*',48X,'*',/,50X,50('*'),/,
     C50X,'*',48X,'*',/,50X,'*',9X,'INPUT',9X,'*',7X,'CALCULATED',7X,'*'
     C,/,50X,'*',23X,'*',24X,'*',/,50X,50('*'),/,50X,'*',11X,'*',11X,'*'
     C,11X,'*',12X,'*',/,50X,'*',5X,'X',5X,'*',5X,'Y',5X,'*',5X,'X',5X,'
     C*',5X,'Y',6X,'*',/,50X,50('*'),/,50X,'*',11X,'*',11X,'*',11X,'*',1
     C2X,'*',/,5(50X,'*',F8.2,3X,'*',F8.2,3X,'*',F8.2,3X,'*',F8.2,4X,'*'
     C,/),6(50X,'*',11X,'*',11X,'*',F8.2,3X,'*',F8.2,4X,'*',/),50X,50('*
     C'),/,'0')
      GO TO 20
 30    NLINES=I-1
      READ (N,4003) IPLT, (XSCL(K),K=1,4)
4003  FORMAT (I5,4F10.2)
C     CALCULATE AN AVERAGE FORM COEF. FOR FORWARD PORTION OF SHIP
      CALL KEFFEC (VK,AVGK)
      WRITE (M,1011) AVGK
1011  FORMAT ('0',39X,50('*'),/,40X,'*',48X,'*',/,40X,'*',
     C 6X,'AVERAGE HULL SHAPE FACTOR = ',F8.5,6X,'*',/,
     C40X,'*',48X,'*',/,40X,50('*'),//)
C     READ IN INTEGERS FOR CONTROL OF OUTPET OPTIONS
  100 READ (N,1000) I09,I03,I05,I06,I07,I010
      IF (I09.LT.1) GO TO 1
      READ (N,1007) (T(I),I=1,20)
 1007 FORMAT (20A4)
      NSTA=NLINES
      WRITE (M,1020) (T(I),I=1,20)
 1020 FORMAT ('1',1X,20A4,//)
      READ (N,1008) FROUDE,SPEED,SEA,HF,HA,CB,VAFT,VTHR
 1008 FORMAT (8F10.5)
      READ (N,4000) TSTORM
4000  FORMAT (F10.5)
      HSIG=SEA*ALBP
      IF (TSTORM.GT.0.01) GO TO 501
      IF (HSIG.LE.35.) GO TO 500
      TSTORM=50.0-1.0*HSIG
      GO TO 501
500   TSTORM=78.0-1.8*HSIG
      IF (HSIG.GE.20.) GO TO 501
      TSTORM=45.-0.15*HSIG
  501 CONTINUE
      IF (FROUDE.GT.0.00001) GO TO 110
      FROUDE = SPEED*1.6889/SQRT(32.174*ALWL)
  110 SPEED = FROUDE*SQRT(32.174*ALWL)/1.6889
      FSCALE=SQRT(ALBP/520.)
      THETA =(HA-HF)/ALBP
      VAFTS=VAFT*FSCALE
      VTHRS=VTHR*FSCALE
      ALB=ALBP/(2.*BB)
      ABT=4.*BB/(HA+HF)
      IF (I05.EQ.1) GO TO 103
      READ (N,1008) (RM(I),RV(I),I=2,8,6)
C     CALCULATE THE RELATIVE MOTIONS AND VELOCITIES AT ALL HALF-STATIONS
      CALL RELMV (RM,RV)
      GO TO 104
```

```
103    NR=0
122    IF(NR.GE.NSTA) GO TO 104
       READ (N,1008) RM(NR+1),RV(NR+1),RM(NR+2),RV(NR+2),RM(NR+3),
      CRV(NR+3),RM(NR+4),RV(NR+4)
       NR=NR+4
       GO TO 122
104    CONTINUE
C      CALCULATE SLAM PRESSURES AT THE KEEL, NUMBER OF SLAMS, EXTENT OF
C      SLAM, VELOCITIES OF SLAM, AND PROBABILITY OF SLAM
       CALL SLAMPR (RM,RV,HF,HA,ALWL,NSTA,EPRES,VK,SLAMS,PROBPR,DVEL,VTHR
      CS,TSTORM,HSIG,PRSLAM,PVEL,STASP)
       NCENTR = NSTA/2 +1
       IF (VAFT.GT.0.01) GO TO 105
       IF (NSTA.EQ.0) GO TO 105
       H1=(1.-SIN((PI/2.)-0.0714*FLOAT(NSTA)))*HSIG/2.
       IF (I06.EQ.0) GO TO 106
       TT=H1/PVEL(NCENTR)
       GO TO 107
106    TT=H1/DVEL(NCENTR)
107    VAFTS=FLOAT(NSTA)*STASP/(4.*TT)
       VAFT=VAFTS/FSCALE
105    IF (NSTA.EQ.0.AND.I03.EQ.1) READ (N,1089) JJJ
1089   FORMAT (I3)
       WRITE (M,1014) CB,FROUDE,SPEED,ALB,ABT,SEA,HSIG,TSTORM,THETA,HF,HA
      C,NLINES,NSTA
 1014 FORMAT ('0',19X,'THE SHIP OPERATING CONDITIONS ARE:',//,
      C20X,'BLOCK COEF. = ',F7.4,/,
      C20X,'FROUDE NO. = ',F7.4,25X,'SHIP VELOCITY = ',F6.2,' KNOTS',/,
      C20X,'LENGTH TO BEAM RATIO = ',F6.3,/,
      C20X,'BEAM TO DRAFT RATIO = ',F6.3,/,
      C20X,'NON-DIMENSIONAL SEA STATE = ',F7.4,10X,'SIGNIFICANT WAVE HEIG
      CHT = ',F5.0,' FEET',/,
      C20X,'TIME OF STORM = ',F5.0,' HOURS',/,
      C20X,'TRIM ANGLE (RADIANS) = ',F7.4,/,
      C20X,'DRAFT FORWARD = ',F5.2,24X,'DRAFT AFT = ',F5.2,/,
      C20X,'NUMBER OF SHIPS LINES READ = ',I3,13X,'NUMBER OF HALF STATION
      CS CONSIDERED = ',I3,/)
       WRITE (M,1015) VAFT,VAFTS,VTHR,VTHRS
1015   FORMAT (20X,'TRAVELING VELOCITY = ',F9.1,' FT/SEC FOR 520 FT SHIP
      C',//,
      C20X,'TRAVELING VELOCITY = ',F9.1,' FT/SEC FOR THIS SHIP'//,
      C20X,'THRESHOLD VELOCITY = ',F6.2,' FT/SEC FOR 520 FT SHIP',//,
      C20X,'THRESHOLD VELOCITY = ',F6.1,' FT/SEC FOR THIS SHIP',//,
      C20X,'THE PROBABILITY OF EXCEEDING THESE SLAM FORCES (ALPHA) = 0.01
      C',//)
       IF (NSTA.EQ.0) WRITE (M,3030)
       IF (NSTA.EQ.0) GO TO 100
 3030 FORMAT (40X,'NO SLAM CALCULATIONS PERFORMED SINCE THE',/,40X,
      C'NUMBER OF SLAMS IS LESS THAN 1 FOR ALL STATIONS',//)
       IF (I06.EQ.0) GO TO 150
C      CALCULATE SPATIAL DISTRIBUTION OF PRESSURE ALONG GIRTH
       CALL PRESS (PROBPR,NSTA,PRES,XX,YY,S,XG)
       GO TO 63
  150 CALL PRESS (EPRES,NSTA,PRES,XX,YY,S,XG)
   63 CONTINUE
C      INTEGRATE PRESSURE TO GET FORCES FOR EACH HALF-STATION
       CALL FORCES (FORCE,NSTA,TIME,DELTAT,PRES,XG,ALBP,DVEL,VAFTS,STASP,
```

```
     C              YY,PVEL,I06)
C      CALCULATE HALF-SINE APPROXIMATION WITH EQUAL IMPULSE AND DURATION
C      AT EACH HALF-STATION
       CALL APPROX ( NSTA,FORCE,FMAX,AIMPLS,A,DUR,DELTAT)
       IF (I010.EQ.2) GO TO 3020
       IF (I010.EQ.1) WRITE(M,3012)
 3012 FORMAT ('1',126('*'),/,1X,2('*',9X),'*',14X,'*',17X,'*',6(11X,'*')
      C,/,1X,2('*',9X),'*','  REL MOTION  *  EXT  PRESSURE  *',11X,
      C'*  MAXIMUM  *',11X,'* AMPLITUDE *',11X,'*     TIME    *',/,
      C1X,'*   HALF  *   FORM  ',34('*'),'   NUMBER  *    SLAM   *    SLA
      CM   *  OF SINE  *    SLAM   *    SLAM   *',/,
      C1X,'* STATION *    COEF  * REL VELOCITY * MOST PROB PRESS *  OF SLA
      CMS *   FORCE   *  IMPULSE  *   APPROX  *  DURATION *   STARTS  *',
      C/,1X,'*',9X,'*     (K)    *    (NON-DIM)   *',6X,'(PSI)',6X,'*',11X,
      C'*    (KIPS)   * (KIP-SEC) *    (KIPS)   *',2('     (SEC)    *'),/,
      C1X,126('*'))
       IF (I010.EQ.1) WRITE (M,3013) (J,VK(J),RM(J),EPRES(J),SLAMS(J),
      CFMAX(J),AIMPLS(J),A(J),DUR(J),TIME(J),RV(J),PROBPR(J),J=1,NSTA)
 3013 FORMAT(17(1X,'*',3X,I3,3X,'*',2X,F6.3,' *',4X,F6.3,4X,'*',6X,F6.1,
      C5X,
      C'*',2(1X,F9.0,1X,'*'),2X,F8.1,1X,'*',2X,F8.0,1X,'*',2(3X,F6.3,2X,
      C'*'),/,1X,'*',2(9X,'*'),4X,F6.3,4X,'*',6X,F6.1,5X,'*',6(11X,'*'),
      C/,1X,126('*'),/))
       IF (I010.EQ.0) GO TO 3015
       IF (I06.EQ.0) WRITE (M,3011)
       IF (I06.EQ.1) WRITE (M,3014)
 3011 FORMAT (30X,'*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***',
      C//)
 3014 FORMAT (30X,'*** MOST PROBABLE PRESSURE USED IN FORCE CALCULATIONS
      C ***',//)
       GO TO 3020
 3015 DO 3000 KM=1,NSTA
      TM(1)=TIME(KM)
      DO 3006 KN=2,20
 3006 TM(KN)= TM(KN-1) + DELTAT
      WRITE (M,3001) KM
      IF (I07.EQ.0) GO TO 3010
      IF (I06.EQ.0) WRITE (M,3002)
      IF (I06.EQ.1) WRITE (M,3004)
      WRITE (M,3005) (TM(J),FORCE(KM,J),J=1,20)
      WRITE (M,3007)
 3010 CONTINUE
      WRITE (M,3008) EPRES(KM),PROBPR(KM),VK(KM)
      WRITE (M,3009) RM(KM),RV(KM),SLAMS(KM),PRSLAM(KM),DVEL(KM),
     C      PVFL(KM),FMAX(KM),AIMPLS(KM),A(KM),DUR(KM),TIME(KM)
 3009 FORMAT (30X,'NON-DIMENSIONAL RELATIVE MOTION = ',F7.4,/,
      C30X,'NON-DIMENSIONAL RELATIVE VELOCITY = ',F7.4,/,
      C30X,'NUMBER OF SLAMS DURING EXTREME STORM = ',F8.0,/,
      C30X,'PROBABILITY OF SLAM IMPACT = ',F8.5,/,
      C30X,'EXTREME RELATIVE VELOCITY = ',F8.1,' FT/SEC',/,
      C30X,'MOST PROBABLE RELATIVE VELECITY = ',F8.1,' FT/SEC',//,
      C30X,'MAXIMUM VALUE OF SLAM FORCE = ',F10.1,' KIPS',/,
      C30X,'IMPULSE VALUE = ',F10.0,' KIP-SEC',/,
      C30X,'AMPLITUDE OF SINE APPROXIMATION = ',F10.1,' KIPS',/,
      C30X,'DURATION OF SLAM IMPACT FORCE = ',F8.5,' SEC',/,
      C30X,'TIME SLAM STARTS = ',F8.5,' SEC',//)
       IF (I06.EQ.0) WRITE (M,3011)
       IF (I06.EQ.1) WRITE (M,3014)
 3000 CONTINUE
```

```
3020 CONTINUE
3001 FORMAT ('1',29X,40('*'),/,30X,'*',38X,'*',/,30X,'*',10X,'HALF STAT
    CION  ',I3,11X,'*',/,30X,'*',38X,'*',/,30X,40('*'))
3002 FORMAT (30X,'*',17X,'*',3X,'EXTREME  FORCE',3X,'*',/,30X,'*',3X,'T
    CIME  (SEC)',3X,'*',5X,'FOR DESIGN',5X,'*',/,30X,'*',17X,'*',7X,'(K
    CIPS)',7X,'*',/,30X,40('*'),/,30X,'*',17X,'*',20X,'*')
3004 FORMAT (30X,'*',17X,'*',3X,'MOST  PROBABLE',3X,'*',/,30X,'*',3X,'T
    CIME  (SEC)',3X,'*',5X,'   FORCE  ',5X,'*',/,30X,'*',17X,'*',7X,'(K
    CIPS)',7X,'*',/,30X,40('*'),/,30X,'*',17X,'*',20X,'*')
3005 FORMAT (30X,'*',5X,F7.3,5X,'*',6X,F8.1,6X,'*',)
3007 FORMAT (30X,40('*'),//)
3008 FORMAT (30X,'EXTREME PRESSURE = ',F10.0,' PSI',/,30X,'MOST PROBABL
    CE PRESSURE = ',F10.0,' PSI',/,30X,'FORM COEF. (K) =',F10.5,/)
     TIMPLS=0.0
     DO 200 I=1,NSTA
 200 TIMPLS=TIMPLS + AIMPLS(I)
     TSLAMT=TIME(NCENTR)+DUR(NCENTR)
     TTT=TIMPLS
     TA = PI*TIMPLS/(2.*TSLAMT)
     LOCI=NCENTR
     WRITE (M,1017) TA,TSLAMT
1017 FORMAT (20X,' AVERAGE SLAM FORCE = ',F8.0,'*SINE(PI*T/',F6.4,')
    C KIPS',//)
     WRITE (M,1018) LOCI
1018 FORMAT (25X,'MIDPOINT LOCATION IS HALF-STATION',I4,///)
     TIMPLS = 0.0
     DO 202 I=1,NSTA
 202 TIMPLS=TIMPLS+AIMPLS(I)*SHAPE(I)
     TB=PI*TIMPLS/(2.*TSLAMT)
     WRITE (M,1019) TB,TSLAMT
1019 FORMAT (20X,'MODAL AVERAGE SLAM FORCE = ',F8.0,'*SINE(PI*T/',F6.4
    C,')     KIPS'//)
     WRITE (M,1018) LOCI
     WRITE (M,1069) TTT
1069 FORMAT ('0',10X,'TOTAL SLAM IMPULSE = ',F8.0,' KIP-SEC',///)
     IF (IO3.EQ.0) GO TO 100
C    CALL PLOTTING ROUTINE FOR TIME HISTORY OF FORCES
     CALL PLOT (TIME,FORCE,DELTAT,NSTA,IPLT,XSCL)
     GO TO 100
 999 WRITE (M,1010)
1010 FORMAT ('0',' END OF JOB')
     STOP
     END
```

```
      SUBROUTINE UGLYDK (NIN,NOUT,XIN,YIN,XOUT,YOUT,ESL,ESR)
C     THIS SUBROUTINE TAKES THE OFFSETS AT EACH INPUT WATERLINE AND
C     USES SPLINE-CUBIC INTERPOLATION TO DETERMINE THE 10 EQUALLY
C     SPACED WATERLINE OFFSETS BETWEEN BL AND 1/10 DESIGN DRAFT
      REAL*8 H,D,A,S,AE,BE,CE,DE,HALF,TWO,SIX,RAD,SLP,DSIN,DCOS
      DIMENSION XIN(5),YIN(5),XOUT(11),YOUT(11),H(5),D(5),A(25),S(5),
     C          AE(5),BE(5),CE(5),DE(5)
      DATA HALF/0.5D00/,TWO/2.0D00/,SIX/6.0D00/,RAD/1.745329250-02/
      NM1=NIN-1
      NM2=NM1-1
      NEQ=NM2
      DO 1 N=1,NM1
      H(N)=XIN(N+1)-XIN(N)
    1 D(N)=(YIN(N+1)-YIN(N))/H(N)
      IF (ESL.GT.90.0) GO TO 2
      NEQ=NEQ+1
    2 IF (ESR.GE.90.0) GO TO 3
      NEQ=NEQ+1
    3 NSQ=NEQ**2
      DO 4 N=1,NSQ
    4 A(N)=0.0
      J=1
      L=1
      IF (ESL.GE.90.0) GO TO 6
      A(1)=TWO*H(1)
      A(2)=H(1)
      SLP=ESL*RAD
      S(1)=(D(1)-(DSIN(SLP)/DCOS(SLP)))*SIX
      J=J+1
      M=L+NEQ
      A(M)=H(1)
      L=M+1
    6 DO 5 N=1,NM2
      IF (N.GT.1) A(L-1)=H(N)
      A(L)=TWO*(H(N)+H(N+1))
      IF (N.LT.NM2) A(L+1)=H(N+1)
      S(J)=(D(N+1)-D(N))*SIX
      J=J+1
    5 L=L+NEQ+1
      IF (ESR.GE.90.0) GO TO 7
      A(L-1)=H(NM1)
      A(L)=-TWO*H(NM1)
      L=L-NEQ
      A(L)=-H(NM1)
      SLP=ESR*RAD
      S(J)=(D(NM1)+(DSIN(SLP)/DCOS(SLP)))*SIX
    7 CALL SIMQ (A,S,NEQ,KERROR)
      IF (ESL.LT.90.) GO TO 8
      DO 9 N=1,NM2
      M=NM2-N+2
    9 S(M)=S(M-1)
      S(1)=0.0
    8 IF (ESR.GT.90.0) S(NIN)=0.0
      DO 10 N=1,NM1
      AE(N)=(S(N+1)-S(N))/(SIX*H(N))
      BE(N)=HALF*S(N)
      CE(N)=D(N)-H(N)*(TWO*S(N)+S(N+1))/SIX
   10 DE(N)=YIN(N)
      J=1
```

```
      DO 11 N=1,NOUT
      IF (XOUT(N).GE.XIN(2)) GO TO 14
      J=1
      GO TO 15
   14 IF (XOUT(N).LT.XIN(NM1)) GO TO 16
      J=NM1
      GO TO 15
   16 IF (XOUT(N).GE.XIN(J+1)) GO TO 12
   15 H1=XOUT(N)-XIN(J)
      H2=H1**2
      H3=H1*H2
      YOUT(N)=AE(J)*H3+BE(J)*H2+CE(J)*H1+DE(J)
      GO TO 11
   12 J=J+1
      GO TO 16
   11 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SPOO (X,VKK,B,H,S,BB,HH,IAOP,ISTA)
```

```
      SUBROUTINE SPOO (X,VKK,B,H,S,BB,HH,IAOP,ISTA)
```


```
C     THIS PROGRAM CALCULATES THE FORM COEF. K DEVELOPED BY OCHI TO BE
C     USED IN PREDICTING THE SLAM CHARACTERISTICS OF A SHIP FROM THE
C     SHIPS LINES.      REFERENCE SNAME TRANSACTIONS 1973
      DIMENSION         X(11),XM(11),YM(11),ZM(11),ROOT(5),W(6),
     2                  XN(11),ZN(11),X1(11),X2(11),Z1(11),Z2(11)
     2            ,WW(6),ROOTR(5),ROOTI(5),COL(6)
      DATA PI/3.1415926/,EPS/0.0005/,N/8/,M/5/
      IF (IAOP.EQ.1) WRITE(M,1001) B,H,BB,HH
      IF (IAOP.EQ.1) WRITE(M,1011) (X(I),I=1,11)
      IF (IAOP.EQ.1) WRITE (M,1002) ISTA
1002  FORMAT (28X,' HALF-STATION NUMBER  ',I3,/)
C
C     CALCULATE AREA AND MOMENT OF INERTIA BY SIMPSON'S RULE.
C
      A=0.
      DO 10 I=2,8,2
   10 A=A+4.*X(I)+2.*X(I+1)
      A=2.*S/3.*(A+X(1)+X(11)+4.*X(10))
      TI=0.0
      AI=0.0
      DO 20 I=2,8,2
      AI=AI+1.
      TI=TI+4.*X(I)*(AI*S)**2 + 2.*X(I+1)*((AI+1.)*S)**2
   20 AI=AI+1.
      TI= 2.*S/3.*(TI+4.*X(10)*(9.*S)**2+X(11)*(10.*S)**2)
C
C     DETERMINE A1,A3,A5, AND U.
C
      DL=H/B
      IF (ABS(DL-1.) .LE. EPS) DL=DL+EPS
      A=A*2./PI
      C2=TI*8./PI
      TK1=B**2*(1.+DL+DL**2)
      TK2=B*(1.-DL)
      TK3=-3.*B*(1.+DL)
      TK4=(A+TK1)/TK2
      TK5=TK3/TK2
      TK6=2./TK2
      D1=DL**2+4.*DL-7.
      D2=-DL**3+DL**2 -3.*DL+3.
      D3=-DL+5.
      D4=DL**3+DL**2+3.*DL+3.
      D5=-DL**2-9.*DL-12.
      D6=3.*DL+7.
      D7=-1.75*DL**4-0.5*DL**3-DL**2-1.5*DL-1.25
      W(1)=-4.*TK6
      W(2)=2.*B*TK6*D3-4.*TK5-6.
      W(3)=B*(2.*(D6+TK5*D3)+B*TK6*D1)-4.*TK4
      W(4)=B*(2.*TK4*D3+B*(D5+TK5*D1+0.5*B*TK6*D2))
      W(5)=B**2*(TK4*D1+0.5*B*(3.*D4+TK5*D2))
      W(6)=0.5*B**3*(TK4*D2+B*D7)-C2
      IF (IAOP.EQ.1) WRITE (M,3000) (W(I),I=1,6)
 3000 FORMAT ('  W= ',6(E15.5,3X),/)
      MM=5
      DO 30 I=1,6
      J=7-I
      WW(I)=W(J)
```

```
   30  CONTINUE
       CALL BAIRS (WW,COL,MM,ROOTR,ROOTI,KK)
       ERROR=0.000001
       NR=0
       DO 40 I=1,5
       ROOT(I)=0.0
       IF (ABS(ROOTI(I)).GT.ERROR) GO TO 40
       IF (ABS(ROOTR(I)).LT.ERROR) GO TO 40
       NR=NR+1
       ROOT(NR)=ROOTR(I)
    40 CONTINUE
       IF (NR.EQ.1) GO TO 39
       DO 38 J=1,3
       KB=J+I
       DO 37 I=KB,NR
       IF (ROOT(J).GT.ROOT(I)) GO TO 37
       R=ROOT(J)
       ROOT(J)=ROOT(I)
       ROOT(I)=R
   37  CONTINUE
   38  CONTINUE
       IF (NR.EQ.4) GO TO 39
       IF (ROOT(4).GT.ROOT(5)) GO TO 39
       R=ROOT(4)
       ROOT(4)=ROOT(5)
       ROOT(5)=R
   39  CONTINUE
       IF (IAOP.EQ.1) WRITE(M,3001) (ROOT(I),I=1,5),NR,KK
 3001  FORMAT ('  ROOT = ',5(F10.5,3X),/,' NR =  ',I5,'  KK = ',I5,/)
       IF (KK.GE.1) GO TO 998
       DO 25 I=1,NR
       U=ROOT(I)
       ALFA=2.*U/B
       A5=TK4/U+TK5+TK6*U
       A1=(1.-DL)/ALFA-A5
       A3=(1.+DL)/ALFA-1.
       IF (IAOP.EQ.1) WRITE (M,3002) A1,A3,A5
 3002  FORMAT ('  A1 = ',F10.5,3X,'A3 = ',F10.5,3X,'A5 = ',F10.5,/)
       IF (A3 .LT. 0.) GO TO 25
       IF (ABS(A1-EPS) .LE. 1. .AND. ABS(A3-EPS) .LE. 1. .AND.
     2  ABS(A5-EPS) .LE. 1.) GO TO 26
    25 CONTINUE
       GO TO 998
C
C      COMPUTE K-VALUE
C
    26 TK=-3.59893 + 2.41988*A1 - 0.872855*A3 + 9.62395*A5
       VK=EXP(TK)
       VKK=VK
       IF(IAOP.GT.0) WRITE (M,2000) A1,A3,A5,U,VK
       IF (IAOP.GT.0) WRITE (M,2004)
       A=A*PI/4.
       IF (IAOP.EQ.1) WRITE (M,3005) A
 3005  FORMAT (1X,'  HALF-SECTION AREA OF 1/10 DRAFT = ',F10.5,/)
       IF (VK.LE.0.19) GO TO 109
       VKK= 0.027*B*B/A
       IF (IAOP.EQ.1) WRITE (M,3004) VKK
```

```
3004 FORMAT (1X,' THE REGRESSION ANALYSIS K NOT USED ----',/,1X,' K = '
    C,F10.6,3X,' WHERE K = 0.027 *B*B/A',/)
 109  CONTINUE
     GO TO 100
 998 WRITE (M,2002)
 100 CONTINUE
     RETURN
1001  FORMAT (1H1,58X,12H*** SPOO ***  //28X,72HTHIS PROGRAM COMPUTES T
    2HE CONFORMAL MAPPING COEFFICIENTS AND THE K-VALUE/28X,
    2 63HNEEDED TO COMPUTE SLAMMING PRESSURE BY THE REGRESSION EQUATION
    2,             //28X,14HHALF BREADTH = ,F10.5,5H FEET,3X,
    2 25HHEIGHT ABOVE THE BOTTOM = ,F10.5,5H FEET,/28X,14HHALF BEAM
    2= ,F10.5,5H FEET,21X,7HDRAFT = ,F10.5,5H FEET)
1011  FORMAT (/ 28X,31HTHE VALUES X ,X ,..... X   ARE ,F10.5/40X,1H0,
    2 3X,1H1,7X,2H10,5X, 9(F10.5/59X),F10.5,5H FEET)
2000  FORMAT (///28X,74HTHE COEFFICIENTS OF THE TRANSFORMATION OF THE C
    2IRCLE IN THE ZETA-PLANE ARE//28X,5HA  = ,E15.8,7X,5HA  = ,E15.8,
    2 7X,5HA  = ,E15.8/29X,1H1,26X,1H3,26X,1H5///28X,19HTHE SCALE FACTO
    2R IS,41X,14HTHE K-VALUE IS//28X,4HU =  ,E15.8,36X,4HK =  ,E15.8)
2002  FORMAT (///28X,66HA SOLUTION FOR U HAS NOT BEEN FOUND.  PLEASE CH
    2ECK THE INPUT DATA.//)
2004  FORMAT (/36X,57HWHERE  K = EXP (- 3.599 + 2.420 A  - 0.873 A  + 9
    2.624 A )  /69X,1H1,10X,1H3,10X,1H5)
      END
```

```
      SUBROUTINE SLAMPR (RM,RV,HF,HA,ALWL,ISTA,EPRES,VK,SLAMS,PROBPR,
     C              DVEL,VTHRS,TSTORM,HSIG,PRSLAM,PVEL,STASP)
C     THIS SUBROUTINE CALCULATES THE EXTREME PRESSURE AT EACH STATION
C     WHERE THE PROPABILITY OF SLAM IMPACT IS GREATER THAN 1
      DIMENSION RM(17),RV(17),EPRES(17),VK(17),PROBPR(17),DVEL(17),
     CPRSLAM(17),SLAMS(17),PVEL(17),X(17)
      DATA ALPHA,G,PI/0.01,32.174,3.1415926/
      DATA M,N/5,8/
      RSTARS=VTHRS**2
      AL=0.983*ALWL
      T=TSTORM
      NSTA=ISTA
      DO 10 I=1,NSTA
      H=((HA-HF)/40.)*FLOAT(I)+HF
      DRM=2.*((AL*RM(I)*0.83)**2)
      DRV=2.*G*AL*(RV(I)*0.83)**2
      PRSLAM(I)=EXP(-H*H/DRM-RSTARS/DRV)
      SLAMS(I)=(3600.*T/(2.*PI))*SQRT(DRV/DRM)*PRSLAM(I)
      IF (SLAMS(I).GE.1.) GO TO 11
      ISTA=I-1
      NSTA=ISTA + 1
      WRITE (M,1002) NSTA,TSTORM,SLAMS(I),HSIG
 1002 FORMAT ('0',' THE NUMBER OF SLAMS AT HALF STATION ',I3,' DURING A
     CSTORM OF DURATION ',F3.0,' HOURS = ',F7.4,/,'  FOR A SIGNIFICANT W
     CAVE HEIGHT OF ',F5.0,' FEET',//)
      GO TO 100
   11 EX=1./SLAMS(I)
      EPRES(I)=VK(I)*(RSTARS-DRV*ALOG(1.-(1.-ALPHA)**EX))
      PROBPR(I)=VK(I)*(RSTARS + DRV*ALOG(SLAMS(I)))
      DVEL(I)=SQRT(EPRES(I)/VK(I))
      PVEL(I)=SQRT(PROBPR(I)/VK(I))
   10 CONTINUE
      ISTA=NSTA
      WRITE (M,1001) ISTA,SLAMS(ISTA),TSTORM,HSIG
 1001 FORMAT ('1',' ADDITIONAL STATIONS SHOULD BE CONSIDERED SINCE AT HA
     CLF STATION ',I3,/,' THE NUMBER OF SLAMS = ',F5.1,' FOR A STORM OF
     CDURATION ',F5.0,' HOURS',/,' THE SIGNIFICANT WAVE HEIGHT = ',F5.0,
     C' FEET',//)
      RETURN
100   CONTINUE
      NCENTR=ISTA/2+1
      HSTASP=STASP/2.
      XCENTR=FLOAT(NCENTR)*HSTASP-HSTASP/2.
      DO 1 J=1,NCENTR
      X(J)=XCENTR-(FLOAT(J)*HSTASP-HSTASP/2.)
1     CONTINUE
      J=NCENTR+1
      DO 2 I=J,NSTA
      X(I)=X(I-1)+HSTASP
2     CONTINUE
      DO 5 I=1,ISTA
      A=-112.*HSIG*X(I)/(AL**2)
      EPRES(I)=EPRES(I)*(10.**A)
      PROBPR(I)=PROBPR(I)*(10.**A)
5     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE RELMV (RM,RV)
C     THIS SUBROUTINE TAKES THE INPUTED RELATIVE MOTIONS AND VELOCITIES
C     AT STATIONS 1 & 4 AND ASSUMES LINEAR VARIATION TO DETERMINE VALUES
C     AT THE 17 HALF-STATIONS
      DIMENSION RM(17),RV(17)
      SLOPE=(RM(8)-RM(2))/6.
      B=RM(2)-SLOPE*2.
      DO 10 I=1,17
      RM(I)=SLOPE*FLOAT(I)+B
   10 CONTINUE
      SLOPE = (RV(8)-RV(2))/6.
      B=RV(2)-SLOPE*2.
      DO 20 I=1,17
      RV(I)=SLOPE*FLOAT(I) + B
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FORCES (FORCE,NSTA,TIME,DELTAT,PRES,XX,ALBP,DVEL,VAFTS,
     C                  STASP,YY,PVEL,I06)
C     THIS SUBROUTINE DOES THE SPATIAL AND TEMPORAL INTEGRATIONS AT EACH
C     HALF-STATION OF THE PRESSURES TO FIND THE SLAM FORCE TIME HISTORY
      DIMENSION FORCE(17,20),PRES(17,11),XX(17,11),TIME(17),DVEL(17),
     C        YY(17),PVEL(17),F(10),FOR(17,20)
      TSLAM=0.1*SQRT(ALBP/520.)
      DELTAT=TSLAM/10.
      NDELT=INT(STASP/(2.*VAFTS*DELTAT))
      IF (NDELT.LT.1) NDELT=1
      T=STASP/(VAFTS*2.)
      NCENTR=NSTA/2+1
      TIME(1)=0.0
      DO 4 I=2,NCENTR
      TIME(I)=TIME(I-1)+T
4     CONTINUE
      I=NCENTR+1
      DO 5 J=I,NSTA
      TIME(J)=TIME(J-1)-T
5     CONTINUE
      DO 20 I=1,NSTA
      IF (I06.EQ.1) GO TO 50
      DELY=DELTAT*DVEL(I)
      GO TO 51
   50 DELY=DELTAT*PVEL(I)
   51 FORCE (I,1)=0.0
      DO 21 J=2,5
   21 FORCE(I,J)=(FLOAT(J-1)/5.)*(PRES(I,1)*XX(I,1) + PRES(I,2)*(XX(I,2)
     C-XX(I,1)))
      DO 22 J=6,10
   22 FORCE(I,J)=(FLOAT(11-J)/5.)*(PRES(I,1)*XX(I,1) + PRES(I,2)*(XX(I,2
     C)-XX(I,1)))
      DO 28 J=11,20
   28 FORCE(I,J)=0.0
      DO 23 J=3,11
      F(1)=0.0
      DELX=(XX(I,J)-XX(I,J-1))*PRES(I,J)
      DO 24 JJ=2,5
   24 F(JJ)=(FLOAT(JJ-1)/5.)*DELX
      DO 25 JJ=6,10
   25 F(JJ)=(FLOAT(11-JJ)/5.)*DELX
      DO 30 L=1,20
      M=INT(YY(J-1)/(DVEL(I)*FLOAT(L)*DELTAT))
      INC=L
      IF (M.LE.1) GO TO 31
   30 CONTINUE
      GO TO 20
   31 M=INC
      MM=M+9
      IF (MM.GT.20) GO TO 100
      DO 26 JJ=1,10
      K=M+JJ-1
   26 FORCE(I,K)=FORCE(I,K) + F(JJ)
      GO TO 23
  100 IF (M.GE.20) GO TO 20
      MM=20
      K=0
      DO 27 JJ=M,MM
      K=K+1
```

```
 27 FORCE(I,JJ)=FORCE(I,JJ)+F(K)
 23 CONTINUE
    DO 29 J=1,20
    FORCE(I,J)=(STASP*FORCE(I,J)/1000.)*144./FLOAT(NDELT)
29   FOR(I,J)=FORCE(I,J)
 20 CONTINUE
    IF (NDELT.LE.1) RETURN
    DO 60 I=1,NSTA
    NEXT=1
    LAST=0
    DO 70 M=2,NDELT
    NEXT=NEXT+1
    LAST=LAST+1
    DO 80 J=NEXT,20
    JJ=J-LAST
    FORCE(I,J)=FORCE(I,J)+FOR(I,JJ)
80  CONTINUE
70  CONTINUE
60  CONTINUE
    RETURN
    END
```

```
      SUBROUTINE PRESS (EPRES,NSTA,PRES,XX,YY,S,XG)
C
C     THIS SUBROUTINE DETERMINES THE SPATIAL DISTRIBUTION OF THE VERTICAL
C     COMPONENT OF THE PRESSURE AS A FUNCTION OF DISTANCE FROM THE CENTERLINE
C
      DIMENSION EPRES(17),PRES(17,11),XX(17,11),YY(11),CTHETA(10),X(11)
     C,XG(17,11)
      DO 10 I=1,NSTA
      PRES(I,1)=EPRES(I)
      X(1)=XX(I,1)
      DO 12 J=1,10
      DELTAX=XX(I,J+1)-XX(I,J)
      HYP=SQRT(S**2+DELTAX**2)
      X(J+1)=X(J)+HYP
   12 CTHETA(J)=DELTAX/HYP
      DO 13 J=1,11
   13 XG(I,J)=X(J)
      DELTAP=EPRES(I)/10.
      DO 14 J=2,11
      A=FLOAT(J-1)
   14 PRES(I,J)=(EPRES(I)-A*DELTAP)*CTHETA(J-1)
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE KEFFEC (VK,AVGK)
C     THIS SUBROUTINE CALCULATES THE AVERAGE OF THE FIRST 11 HALF-
C     STATIONS CALLED THE AVERAGE FORM COEF.
      DIMENSION VK(17)
      AVGK=0.0
      DO 20 J=1,11
20    AVGK=AVGK+VK(J)
      AVGK=AVGK/11.
      RETURN
      END
```

```
      SUBROUTINE APPROX (NSTA,FORCE,FMAX,AIMPLS,A,DUR,DELTAT)
C     THIS SUBROUTINE CALCULATES FOR EACH HALF-STATION THE IMPULSE BY
C     INTEGRATING THE FORCE TIME HISTORY AND COMPUTES A HALF-SINE
C     APPROXIMATION WITH THE SAME IMPULSE AND DURATION
      DIMENSION FORCE(17,20),FMAX(17),AIMPLS(17),A(17),DUR(17),Y(20)
      DATA PI/3.141592654/
      DO 10 I=1,NSTA
      DO 11 J=10,20
      IF (FORCE(I,J).GE.0.05) GO TO 11
      DUR(I)=FLOAT(J-1)*DELTAT
      NPTS=J
      GO TO 12
   11 CONTINUE
      DUR(I)=20.*DELTAT
   12 DO 13 J=1,20
      Y(J)=FORCE(I,J)
   13 CONTINUE
      CALL MAXFOR (Y,AMAX)
      FMAX(I)=AMAX
      CALL QSF (DELTAT,Y,Y,20)
      AIMPLS(I)=Y(20)
      A(I) = PI*AIMPLS(I)/(2.*DUR(I))
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE MAXFOR (Y,AMAX)
C     THIS SUBROUTINE DETERMINES THE MAXIMUM FORCE FROM THE FORCE TIME
C     HISTORY AT EACH HALF-STATION USING A PARABOLIC FIT THROUGH THE
C     HIGHEST 3 POINTS.
      DIMENSION Y(20)
      FLAST = Y(2)
      DO 10 I=3,8
      N=I
      IF (Y(I).LT.FLAST) GO TO 11
      FLAST = Y(I)
   10  CONTINUE
      AMAX = 1.0E10
   11 AA=Y(N-2)
      BB=Y(N-1)
      CC=Y(N)
      B=0.5*(4.*BB-3.*AA-CC)
      C=AA
      A=BB-AA-B
      X=-B/(2.*A)
      AMAX=A*X**2 + B*X + C
      RETURN
      END
```

```
      SUBROUTINE PLOT (TIME,FORCES,DELTAT,NSTA,IPLT,XSCL)
C     THIS SUBROUTINE USES THE M.I.T. J.C.F.   PICTR PLOTTING ROUTINE
C     - IF THE PROGRAM IS TO BE USED ON ANOTHER MACHINE, THIS IS THE
C     ONLY SUBROUTINE THAT REQUIRES CHANGING ALONG WITH THE RELATED
C     CARDS IN MAIN
      INTEGER*2 IXPLOT(17),XLAB(40)
      DIMENSION PLTR(34,20),TIME(17),FORCES(17,20),XSCL(4)
      DATA IXPLOT/18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34/
      DO 10 I=1,NSTA
      T=TIME(I)
      DO 20 J=1,20
      PLTR(I,J)=FORCES(I,J)
      II=I+17
      PLTR(II,J)=T
   20 T=T+DELTAT
  10  CONTINUE
      CALL PICTR (PLTR,34,XLAB,XSCL,NSTA,20,-1,-1,3,IPLT,0,1,IXPLOT)
      PAUSE
      RETURN
      END
```

```
      SUBROUTINE BAIRS(ACOF,A,NORD,ROOTR,ROOTI,IER)
      REAL ACOF(1),A(1),ROOTR(1),ROOTI(1)
      DATA TOL2/1.0E-3/,TOLX/5.0E-6/
      DATA TOL,ITMIN,ITMAX/1.0E-8,10,100/
      DATA TOL3/1.0E-10/
      N=NORD
      IF(N.LT.0)N=-N
      D=ACOF(N+1)
      DOM=-100.0
      IR=0
C------BASIC ERROR CHECKING
      IF(N)1,1,2
 1    IR=1
      GO TO 200
 2    IF(N-99)4,4,3
 3    IR=2
      GO TO 200
 4    IF(D)6,5,6
 5    IR=4
      GO TO 200
 6    DO 10 I=1,N
 10   A(I)=ACOF(I)/D
      A(N+1)=1.0
C------REMOVE TRIVIAL ZEROES FIRST
      J=2
      DO 14 I=1,N
      IF(A(I))12,11,12
 11   ROOTR(J-1)=0.0
      ROOTI(J-1)=0.0
 14   J=J+1
C------FIND A REAL ROOT IF REDUCED POLYNOM IAL IS ODD
 12   LEFT=N-J+1
      IF(LEFT)100,90,13
 13   NN=N+1
      IJ=J-1
C------ESTIMATE THE MODULUS OF THE LARGEST ROOT
      DO 151 I=IJ,NN
      IF(A(I).NE.0.0)
     1DOM=AMAX1(ALOG(ABS(A(I)/A(IJ)))/FLOAT(I-IJ+1),DOM)
 151  CONTINUE
      DOM=EXP(DOM)
      QJ=1.0/DOM/DOM
      PJ=-2.0/DOM
C      SCALE THE POLYNOMIAL SO LARGEST ROOT IS NEAR 1.0
      DO 9 I=IJ,N
      DO 9 K=IJ,I
 9    A(K)=A(K)/DOM
      IF(LEFT.NE.LEFT/2*2)GO TO 15
 300  X0=0.0
      P0=A(J-1)
C------DETERMINE IF REAL ROOT IS POSITIVE OR NEGATIVE
      X1=1.0
      IF(P0.GE.0.0)X1=-1.0
      IP=1
C------EXPAND RANGE UNTIL ZERO HAS BEEN BRACKETED
C
C------THIS IS AN INTERNAL SUBROUTINE TO EVALUATE A REDUCED POLYNOMIAL
C
 400  ICNT=N+2
```

```
      P1=0.0
 401  P1=P1*X1+A(ICNT-1)
      ICNT=ICNT-1
      IF(ICNT-J)402,401,401
 402  GO TO (320,330),IP
C
 320  IF(P0*P1)325,360,321
 321  X0=X1
      X1=10.0*X1
      GO TO 400
C------ANSWER LIES BETWEEN X0 AND X1
 325  IP=2
      X2=X1
 326  X1=(X0+X2)*0.5
      IF(ABS(X2-X0)-ABS(X1*TOLX))360,360,400
 330  IF(P0*P1)331,360,332
 331  X2=X1
      GO TO 326
 332  X0=X1
      GO TO 326
C------NOW DIVIDE OUT THE ZERO
 360  ROOTR(J-1)=X1*DOM
      ROOTI(J-1)=0.0
      I=N
 370  A(I)=A(I)+X1*A(I+1)
      I=I-1
      IF(I-J)380,370,370
 380   J=J+1
 15   CONTINUE
      DO 80 J=J,N,2
      ITRY=0
      IF(J.LT.N)GO TO 41
      P=A(N)
      Q=A(N-1)
      GO TO 50
 41   IF(NORD.GT.0)GO TO 43
C      TRY PREVIOUS ROOT FOR STARTING POINT
      P=PJ*ROOTR(J)
      Q=QJ*(ROOTR(J)*ROOTR(J)+ROOTI(J)*ROOTI(J))
      GO TO 141
 43   P=0.0
      Q=ITRY
      IF(ITRY.GT.1)GO TO 47
      ITRY=ITRY+1
 141  DO 451 ITER=1,ITMAX
      B0=0.0
      B1=0.0
      C0=0.0
      C1=0.0
      C2=0.0
C------COMPUTE COLUMN OF B'S AND C'S
      I=N+1
 20   DD=A(I)-P*B1-Q*B0
      B0=B1
      B1=DD
      I=I-1
      IF(I-J+2)40,40,30
 30   DD=B1-P*C2-Q*C1
      C0=C1
```

```
      C1=C2
      C2=DD
      GO TO 20
C------SPECIAL FORM FOR LAST COEFFICIENT
 40   C2=-P*C1-Q*C0
      DD=C1*C1-C2*C0
      DP=B0*C1-B1*C0
      DQ=B1*C1-B0*C2
      IF(ABS(DD).LE.ABS(TOL2*DP).OR.ABS(DD).LE.ABS(TOL2*DQ))GO TO 43
      DP=DP/DD
      DQ=DQ/DD
      P=P+DP
      Q=Q+DQ
      ERR=DP*DP+DQ*DQ
      CRIT=P*P+Q*Q
      IF(CRIT.LE.TOL2*ERR)GO TO 43
      CRIT=ERR/CRIT
      IF(ITER.GT.3.AND.CRIT.LT.TOL3)GO TO 50
C------DO AT LEAST ITMIN ITERATIONS
      IF(ITER-ITMIN)45,45,44
C------IF ERROR IS DECREASING, KEEP GOING
 44   IF(CRIT.GE.CRITO)GO TO 46
      IF(CRIT.LT.TOL3)GO TO 50
 45   ERRO=ERR
      CRITO=CRIT
 451  CONTINUE
C------DROP OUT WHEN ERR STARTS TO INCREASE OR ITER IS GREATER THAN ITMAX
 46   IF(CRITO-TOL)50,50,43
C------IF ACCURACY IS INSUFFICIENT, GIVE ERROR OUTPUT AND PROCEED
 47   IR=3
      WRITE(5,5000)ERRO,ERR,CRITO,CRIT
 5000 FORMAT(1P,10G12.4)
 50   PP=-P/2.0
      DISC=PP*PP-Q
      IF(DISC)52,54,54
 52   DISC=SQRT(-DISC)
      ROOTR(J-I)=PP*DOM
      ROOTR(J)=PP*DOM
      ROOTI(J-1)=-DISC*DOM
      ROOTI(J)=DISC*DOM
      GO TO 56
 54   DISC=SQRT(DISC)
      ROOTR(J-I)=(PP-DISC)*DOM
      ROOTR(J)=(PP+DISC)*DOM
      ROOTI(J-I)=0.0
      ROOTI(J)=0.0
C------SYNTHETIC DIVISION WITH QUADRATIC FACTORS
 56   I=N
      JL=J
      A(N)=A(N)-P
 60   I=I-1
      IF(I-J)80,70,70
 70   A(I)=A(I)-P*A(I+1)-Q*A(I+2)
      GO TO 60
 80   CONTINUE
      IF(JL-N)90,100,100
 90   ROOTR(N)=-A(N)
      ROOTI(N)=0.0
 100  CONTINUE
```

```
200   IER=IR
      RETURN
      END
```

APPENDIX C - PROGRAM USER'S MANUAL

This appendix will discuss the calculations performed in the various subroutines, the output format options, and the input data deck.

DESCRIPTION OF PROGRAM

MAIN - The Main program does some simple calculations, contains formats for I/O, determines from the I/O options specified what calculations are to be performed, and calls the appropriate subroutines to perform the calculations.

SUBROUTINE UGLYDK - This subroutine takes the five inputed offsets and uses a spline-cubic curve fitting routine to interpolate ten offsets in equal increments of T'/10 from the base line to T'. The subroutine is called once for each set of inputed offsets. The subroutine requires solution to a set of simultaneous linear equations which is done by the IBM SSP/SIMQ subroutine which should be available to most users.

SUBROUTINE SPOO - This subroutine performs the calculations necessary to find the form coefficient k. For values above $k = 0.19$ equation (6a) is used to determine k. This subroutine performs the mapping necessary to determine the regression analysis form coefficients. This subroutine is called once for each set of inputed offsets. The subroutine requires the roots of a fifth degree polynomial which is accomplished in the BAIRS subroutine.

SUBROUTINE SLAMPR - This subroutine takes the relative motions, relative velocities, form coefficients, significant wave height, and drafts and calculates the following:

1. number of slams at each half-station,
2. longitudinal extent of slam,
3. probability of slam at each half-station,
4. most probable extreme pressure at each half-station,
5. extreme pressure for design at each half-station,
6. and the most probable and extreme velocities of impact at each half-station.

This subroutine uses the various equations developed in Section IV to determine the above information.

SUBROUTINE RELMV - This subroutine takes the non-dimensional relative motions and relative velocities inputed at station 1 and 4 from the tables and uses linear interpolation to find the values for the 17 half-stations. Seventeen half-stations were considered since slam damage has been reported as far as 40% aft of the forward perpendicular. Linear interpolation is valid within the linear theory used in seakeeping programs.

SUBROUTINE FORCES - This subroutine performs the temporal integration of pressure determined by SLAMPR and PRESS subroutines. The output is the pressure time history for each half-station in the slam region.

SUBROUTINE PRESS - This subroutine takes the pressure at the keel from SLAMPR and calculates the girth distribution of vertical pressure assuming linear variation from the flat to T' and resolves the vertical component at each elevation using the hull offsets to calculate the angle β that the normal makes with the vertical (Figures 8a & 8b).

SUBROUTINE KEFFEC - This subroutine is not used in any of the calculations but determines an average hull form coefficient. This value is a measure of a ship's overall susceptibility to slam forces. For two similar ships the one with the larger average k will have larger slam forces and impulses. The average is done over the forward eleven half-stations since slamming rarely occurs aft of this point.

SUBROUTINE APPROX - This subroutine uses Simpson's integration to find the slam impulse by integrating the pressure time history from FORCES at each half-station. This subroutine calls the IBM SSP/QSF subroutine to perform the integrations. Once the impulse is known, the amplitude of an equivalent half-sine pulse with equal duration can be found. This sine approximation is determined to input into the S.H.V.R.S. dynamic analysis program.

SUBROUTINE MAXFOR - This subroutine fits a parabola through the three highest force points at each half-station and the first derivative is set equal to zero to find the maximum force at each half-station.

SUBROUTINE PLOT - This routine uses the M.I.T. Joint Computer Facility PICTR plotting routine to plot the force time history for each half-station on one graph. Figures 9 to 12 are computer plots using this routine. This is the only subroutine that would require changing if running the program on another computer.

OUTPUT OPTIONS

There are several output options available from the program depending on the information desired. Options are specified in the data deck by assigning integer values to integer variables. The following options are available:

1. I01 = 1 This option prints information from the SPOO subroutine to aid in determining problems in this routine. See Figure 22 for the information printed.

   I01 = Ø Delete the above output. This is the normal option.

2. I03 = 1 This option allows a plot of the pressure time history. See Figures 13 to 16 for typical plots.

   I03 = Ø Delete the plots.

3. I04 = 1 This outputs a table of inputed offsets and the ten calculated offsets for each half-station. It is desirable to specify this option the first time a set of lines are read so as to check the data. See Figure 23 for an example output.

   I04 = Ø Delete table of offsets.

4. I06 = 1 This option specifies that the calculations and output values will use most probable extreme pressure values.

   I06 = Ø This option specifies that the program uses the extreme pressure for design.

5. I07 = 1 The force time history is outputed in tabular format. See Figure 24 for an example of the output information.

   I07 = Ø Delete table of forces.

6. I01Ø = Ø Write table of information for each half-station in the slam region. See Figure 25 for the information available in this option.

   I01Ø = 1 Write a single table of information for all the stations in the slam region. Tables 7 to 10 were prepared using this option.

   I01Ø = 2 Delete both of the above tables.

Any combination of the above options may be specified to get the information desired. Since the main cost of running the program is the output cost, it was felt that being able to eliminate unnecessary output information was necessary. Several input options are available:

1. I05 = 1 This allows the inputing of all the relative motions and velocities from seakeeping results if available.

   I05 = Ø Input relative motions and velocities for stations 1 & 4 only. (Non-dimensional values from Tables [15]).

2. Time of storm may be specified if desired. If TSTORM is specified, it will be used in the calculations. If set equal to zero, the TSTORM values will be obtained from Figure 4.
3. The traveling velocity may be specified if desired. The value specified should be for a 520 foot ship and the program will Froude scale this figure. If the traveling velocity (VAFT) is set equal to zero, the traveling velocity will be calculated by the program as discussed in Section IV.
4. The Froude number or the speed in knots can be specified. Both need not be inputed.

DATA DECK

In this section the input format for the data deck will be discussed.

CARD SET #1

CARD 1 - Format (3 I 5) - I01, I02, I04

The values for I01 and I04 are discussed above. I02 is always set equal to 1 and indicates that ships lines follow.

CARD 2 - Format (20 A 4) - Title and information on ship.

This card contains any information desired by the user to designate the ship being run. This data is printed in the output as a heading only and is not used by the program.

CARD 3 - Format (5 F 10.5) - BB, HH, ALBP, ALWL, STASP

BB = Half Beam

HH = Design Draft

ALBP = Length Between Perpendiculars

ALWL = Length of Load Waterline

STASP = Station Spacing (not half-stations)

<u>CARD SET #2</u>

This card set contains the ships lines necessary for slam calculations.

CARD 1 - Format (5 F 10.5)

This card contains the waterlines at which the offsets were taken. The first value must be the 0.0 foot waterline.

CARD 2 - Format (5 F 10.5)

The offsets for the five waterlines in the same order as CARD 1 for the first half-station. CARD 2 is repeated for as many half-stations as desired up to a total of 17 half-stations.

CARD 3 - BLANK CARD

This card indicates that the last set of offsets has been inputed.

<u>CARD SET #3</u>

This set contains only one card. If no plots are desired (I03 = Ø), this card is left blank.

Format (I 5, 4 F 10.5) - IPLT, XSCL

IPLT = +1 - This specifies that the plot routine scales the plots. (AUTOSCALE)

IPLT = -2 - This specifies to the plot routine that the values in XSCL be used to scale the plots.

XSCL(1) = 0.0 = Time slam starts

XSCL(2) = End of time axis

XSCL(3) = 0.0

XSCL(4) = Maximum force on vertical axis.

If IPLT = +1, XSCL need not be specified. This same data will be used to scale all plots until a new set of lines are read.

CARD SET #4

Card set #4 contains the data necessary for a particular set of operating conditions. This set is repeated for as many operating conditions as desired.

CARD 1 - Format (6 I 5) - I09, I03, I05, I06, I07, I01Ø

I09 = 1 always = 1 - indicates a new set of operating conditions follow. The other integer variables were discussed above.

CARD 2 - Format (20 A 4)

This card contains information which is printed on the output to distinguish this operating condition from the others.

CARD 3 - Format (8 F 10.5) - FROUDE, SPEED, SEA, HF, HA, CB, VAFT, VTHR

FROUDE = Froude number

SPEED = Ship speed in knots

SEA = Significant wave height (feet)

HF = Draft Forward (feet)

HA = Draft Aft (feet)

CB = Block coefficient of underwater portion of hull for this draft.

VAFT = Traveling velocity for 520 foot ship (ft/sec)

VTHR = Threshold velocity for 520 foot ship (ft/sec)

CARD 4 - (F 10.5) - TSTORM

TSTORM = Duration of storm in hours

CARD 5 - IF I05 = Ø, Format (4 F 10.5)- RM(2), RV(2), RM(8), RV(8)

RM(2) = relative motion from tables at station 1

RV(2) = relative velocity from tables at station 1

RM(8) = relative motion from tables at station 4

RV(8) = relative velocity from tables at station 4

IF I05 = 1 Format (8 F 10.5) for each card - use as many cards as necessary to specify the non-dimensional relative motions and velocities for as many half-stations as offsets read in Card Set #1. The values are specified in pairs beginning at half-station 1 (i.e., RM(1), RV(1), RM(2), RV(2), ...)

CARD 6 - IF I03 = Ø -- Delete Card

IF I03 = 1 -- FIRST 40 spaces contain X-axis label

NEXT 40 spaces contain Y-axis label

This card is used by plotting subroutine.

At the end of the operating conditions for this ship a blank card is inserted to indicate the end of the calculations for this set of lines. The above card sets 1 to 4 can be repeated for as many ships as desired. After the last ship has been read, another blank card is inserted to indicate the end of the data deck. Therefore the last two cards in the deck will be blank cards indicating the end of the operating conditions and that the last ship has been read.

```
                              *** SPOO ***

          THIS PROGRAM COMPUTES THE CONFORMAL MAPPING COEFFICIENTS AND THE K-VALUE
          NEEDED TO COMPUTE SLAMMING PRESSURE BY THE REGRESSION EQUATION.

          HALF BREADTH =  29.71672 FEET   HEIGHT ABOVE THE BOTTOM =   2.97500 FEET
          HALF BEAM    =  38.00000 FEET                     DRAFT =  29.75000 FEET

          THE VALUES X ,X ,....., X   ARE   29.71672
                      0  1        10        29.26756
                                            28.78240
                                            28.34886
                                            27.89246
                                            27.41539
                                            26.79909
                                            25.83315
                                            24.43604
                                            22.78220
                                            21.00000 FEET
           HALF-STATION NUMBER   15

W=    -0.20916E 00      0.30450E 02     -0.12311E 04      0.24976E 05     -0.23534E 06      0.88614E 06

ROOT =   16.62479     15.48172     13.05476      0.00000      0.00000
NR =       3  KK =       0

A1 =     0.79577   A3 =   -0.01678   A5 =    0.00851

A1 =     0.76103   A3 =    0.05582   A5 =    0.10263


          THE COEFFICIENTS OF THE TRANSFORMATION OF THE CIRCLE IN THE ZETA-PLANE ARE

          A  =  0.76102318E 00        A  =  0.55817604E-01       A  =  0.10262585E 00
           1                           3                          5

          THE SCALE FACTOR IS                                         THE K-VALUE IS

          U =  0.15481722E 02                                     K =  0.44114363E 00

                 WHERE  K = EXP (- 3.599 + 2.420 A  - 0.873 A  + 9.624 A )
                                                  1          3          5
 HALF-SECTION AREA OF 1/10 DRAFT =    79.44501

THE REGRESSION ANALYSIS K NOT USED ----
K =    0.300123    WHERE K = 0.027 *B*B/A
```

FIGURE 22 - INTERMEDIATE OUTPUT FROM SPOO SUBROUTINE (IO1=1)

STATION 4.5 OFFSETS (FEET)

INPUT		CALCULATED	
X	Y	X	Y
6.95	0.00	6.95	0.00
11.00	1.00	8.29	0.30
13.10	2.00	9.55	0.60
14.80	3.00	10.65	.89
16.00	4.00	11.52	1.19
		12.18	1.49
		12.72	1.78
		13.27	2.08
		13.88	2.38
		14.41	2.68
		14.78	2.97

FIGURE 23 - LIST OF INPUTED AND CALCULATED OFFSETS (104:1)

HALF STATION 2

TIME (SEC)	EXTREME FORCE FOR DESIGN (KIPS)
0.050	0.0
0.060	156.7
0.070	413.0
0.080	636.5
0.090	859.9
0.100	1083.3
0.110	913.4
0.120	704.1
0.130	480.6
0.140	257.2
0.150	33.8
0.160	7.0
0.171	0.0
0.181	0.0
0.191	0.0
0.201	0.0
0.211	0.0
0.221	0.0
0.231	0.0
0.241	0.0

FIGURE 24 - FORCE TIME HISTORY (IO7 = 1)

```
*****************************************
*                                       *
*          HALF STATION    4            *
*                                       *
*****************************************
EXTREME PRESSURE =       244. PSI
MOST PROBABLE PRESSURE =       166. PSI
FORM COEF. (K) =   0.07434

NON-DIMENSIONAL RELATIVE MOTION =  0.0238
NON-DIMENSIONAL RELATIVE VELOCITY =  0.0850
NUMBER OF SLAMS DURING EXTREME STORM =    4788.
PROBABILITY OF SLAM IMPACT =  0.27042
EXTREME RELATIVE VELOCITY =      57.3 FT/SEC
MOST PROBABLE RELATIVE VELECITY =      47.2 FT/SEC

MAXIMUM VALUE OF SLAM FORCE =      3543.0 KIPS
IMPULSE VALUE =         183. KIP-SEC
AMPLITUDE OF SINE APPROXIMATION =      2372.0 KIPS
DURATION OF SLAM IMPACT FORCE =  0.12092 SEC
TIME SLAM STARTS =  0.14886 SEC
```

FIGURE 25 - INFORMATION PRINTED AT EACH HALF-STATION (IO1Ø = Ø)

APPENDIX D - EXAMPLE PROGRAM

An example program data deck and sample output are included to aid in using this program. MARINER case 2 is the example run which is the fully loaded case at 15.5 knots.

```
// XEQ SLAMCW
  0    1    0
          MARINFR - - - - - - - - - - - - - - - - - AS BUILT
38.0        29.75      528.0      537.13     26.
0.00        1.00       2.00       3.00       4.00
0.5         1.5        1.75       2.05       2.3
1.00        3.00       3.5        4.1        4.6
1.0         3.45       4.3        5.15       5.6
1.0         3.9        5.1        6.2        6.6
1.5         4.95       6.3        7.5        8.05
2.6         6.0        7.5        8.8        9.5
4.0         7.5        9.2        10.6       11.6
5.4         9.0        10.9       12.4       13.5
6.95        11.0       13.1       14.8       16.0
8.00        12.00      15.00      17.        18.2
8.58        15.        17.6       19.7       21.0
9.17        18.00      20.2       22.3       24.08
13.6        21.        23.10      24.9       26.5
                                                                          BLANK
-2   0.0         0.5        0.0         5000.
  1    1    0    0    0    1
  2  MARINER - F=0.20  S=0.047  CB=0.613  L/B=6.84  B/T=2.81  FULLY LOADED
          15.5       0.047      27.0       27.0        0.613      0.0         12.0
0.0
0.0280      0.095      0.0191     0.069
  2  MARINER           TIME (SEC)                         FORCE (KIPS)
                                                                          BLANK
                                                                          BLANK
// END
```

FIGURE 26a - SAMPLE PROGRAM - DATA DECK

```
THIS PROGRAM CALCULATES THE SLAM FORCE DISTRIBUTION VS TIME
  ON THE LOWER 1/10 OF THE SHIP FROM STATION 8 FORWARD.


MARINER - - - - - - - - - - - - - - AS BUILT

HALF BEAM =    38.00000            DESIGN DRAFT =    29.75000

LBP =      528.00                  LENGTH LOAD WATER LINE =      537.13

DISTANCE BETWEEN STATIONS =  26.00

     (ALL DISTANCES IN FEET)


        ***************************************************
        *                                                 *
        *     AVERAGE HULL SHAPE FACTOR =  0.11909        *
        *                                                 *
        ***************************************************
```

FIGURE 26b - SAMPLE PROGRAM - OUTPUT

```
2  MARINER - F=0.20  S=0.047  CB=0.613  L/B=6.84  B/T=2.81  FULLY LOADED


THE NUMBER OF SLAMS AT HALF STATION  11 DURING A STORM OF DURATION 33. HOURS =  0.3550
FOR A SIGNIFICANT WAVE HEIGHT OF    25. FEET


          THE SHIP OPERATING CONDITIONS ARE:

          BLOCK COEF. =  0.6130
          FROUDE NO. =  0.1991                          SHIP VELOCITY =  15.50 KNOTS
          LENGTH TO BEAM RATIO =  6.947
          BEAM TO DRAFT RATIO =  2.815
          NON-DIMENSIONAL SEA STATE =  0.0470           SIGNIFICANT WAVE HEIGHT =   25. FEET
          TIME OF STORM =   33. HOURS
          TRIM ANGLE (RADIANS) =  0.0000
          DRAFT FORWARD = 27.00                         DRAFT AFT = 27.00
          NUMBER OF SHIPS LINES READ =  13              NUMBER OF HALF STATIONS CONSIDERED =  10

          TRAVELING VELOCITY =     816.0 FT/SEC FOR 520 FT SHIP

          TRAVELING VELOCITY =     822.2 FT/SEC FOR THIS SHIP

          THRESHOLD VELOCITY =  12.00 FT/SEC FOR 520 FT SHIP

          THRESHOLD VELOCITY =   12.1 FT/SEC FOR THIS SHIP

          THE PROBABILITY OF EXCEEDING THESE SLAM FORCES (ALPHA) = 0.01
```

FIGURE 26b - SAMPLE PROGRAM - OUTPUT (cont.)

HALF STATION	FORM COEF (K)	REL MOTION: REL VELOCITY (NON-DIM)	EXT PRESSURE: MOST PROB PRESS (PSI)	NUMBER OF SLAMS	MAXIMUM SLAM FORCE (KIPS)	SLAM IMPULSE (KIP-SEC)	AMPLITUDE OF SINE APPROX (KIPS)	SLAM DURATION (SEC)	TIME SLAM STARTS (SEC)
1	0.024	0.039 0.209	14.7 9.2	956.	77.	3.9	51.	0.121	0.000
2	0.055	0.038 0.205	41.8 25.6	711.	438.	22.3	289.	0.121	0.016
3	0.065	0.037 0.201	59.5 35.9	507.	742.	38.1	495.	0.121	0.032
4	0.074	0.035 0.296	80.4 47.6	340.	1164.	60.2	782.	0.121	0.047
5	0.093	0.034 0.092	118.3 68.3	212.	2116.	111.1	1443.	0.121	0.063
6	0.115	0.032 0.078	169.7 94.9	120.	3741.	195.7	2347.	0.131	0.079
7	0.139	0.031 .073	128.0 68.4	60.	3557.	185.8	2228.	0.131	.063
8	0.157	0.019 .029	88.3 43.9	25.	2957.	154.4	1851.	0.131	0.047
9	0.176	0.018 0.025	58.2 25.7	9.	2324.	123.8	1378.	0.141	0.032
10	0.186	0.016 0.060	34.0 11.9	2.	1517.	82.4	918.	0.141	0.016

*** EXTREME PRESSURE USED IN FORCE CALCULATIONS ***

AVERAGE SLAM FORCE = 7312.*SINE(PI*T/0.2100) KIPS

MIDPOINT LOCATION IS HALF-STATION 6

MODAL AVERAGE SLAM FORCE = 2719.*SINE(PI*T/0.2100) KIPS

MIDPOINT LOCATION IS HALF-STATION 6

TOTAL SLAM IMPULSE = 978. KIP-SEC

FIGURE 26b - SAMPLE PROGRAM - OUTPUT (cont.)

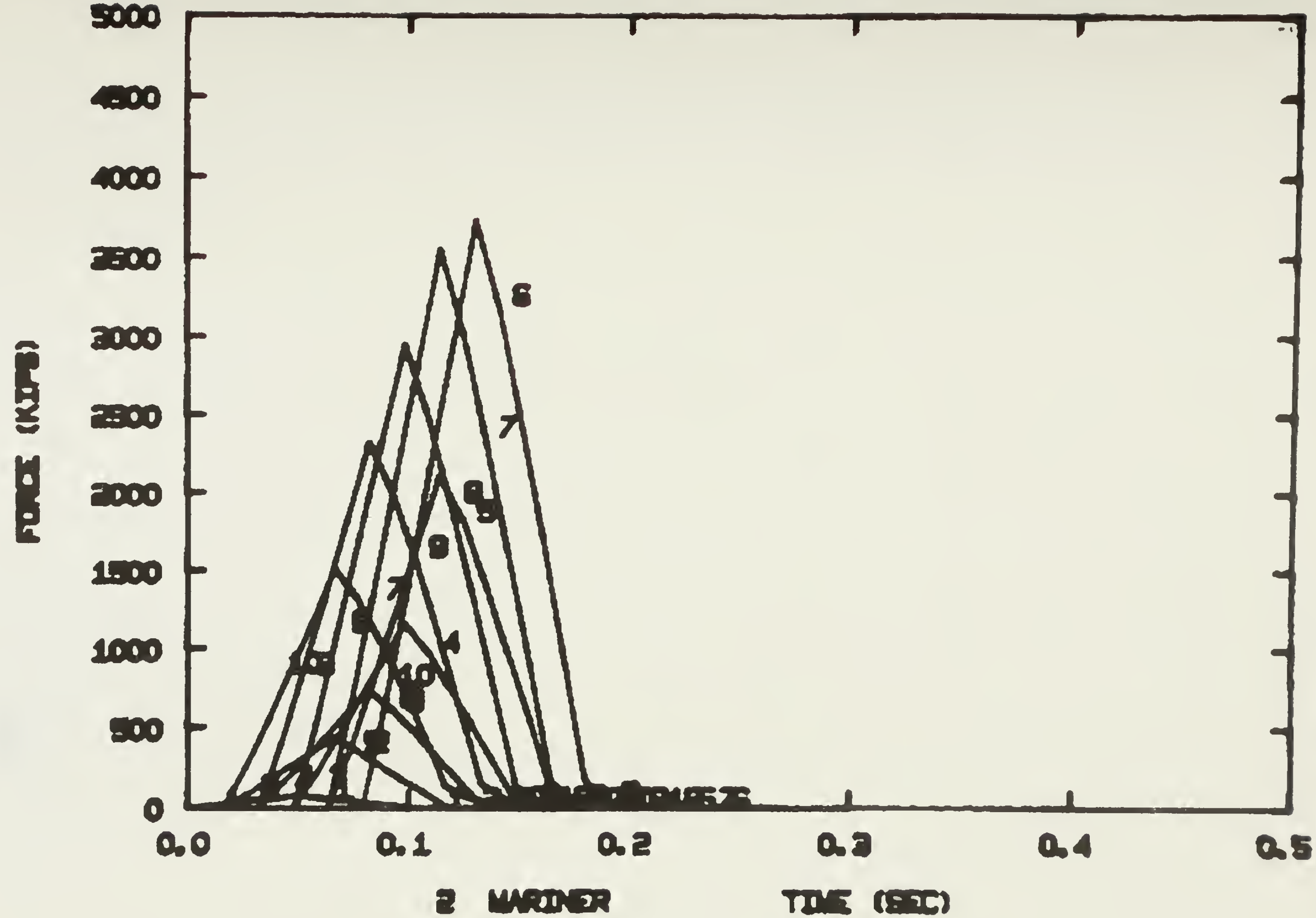

FIGURE 26b - SAMPLE PROGRAM - OUTPUT (cont.)

Thesis 165003
W22223 Walker
Slam loading for
use in hull girder:
response analysis.